



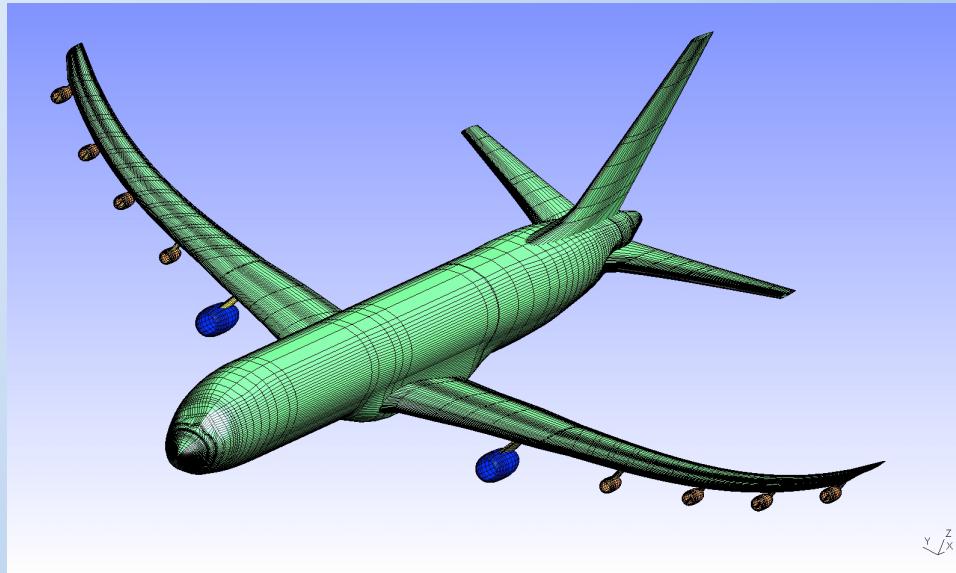
# Wing Shaping Concepts Using Distributed Propulsion For Optimizing Spanwise L/D To Reduce Fuel Burn



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**NASA Aeronautics Research Mission Directorate (ARMD)**  
**2014 Seedling Technical Seminar**  
**February 25, 2014**



# Background and Motivation

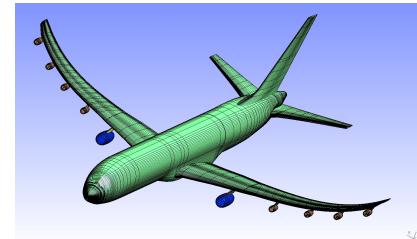


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**Innovation Step:** Exploit multidisciplinary interactions while maintaining aero-structural stability

- **Potential Benefits**

- Mission adaptive wing shaping
- Improved off-design performance
- Potential reduction in system and aircraft weight
- Flutter suppression



**Wing Shaping Concepts** exploit trades between **wing flexibility** and **span efficiency**

- **Potential Benefits**

- Structural weight reduction (20%)
- Fuel burn reduction (3-4%)



**Distributed Propulsion** seeks to improve propulsive efficiency and eliminate control surfaces

- **Potential Benefits**

- Increase by-pass ratio (x3)
- Fuel burn reduction (3-7%)



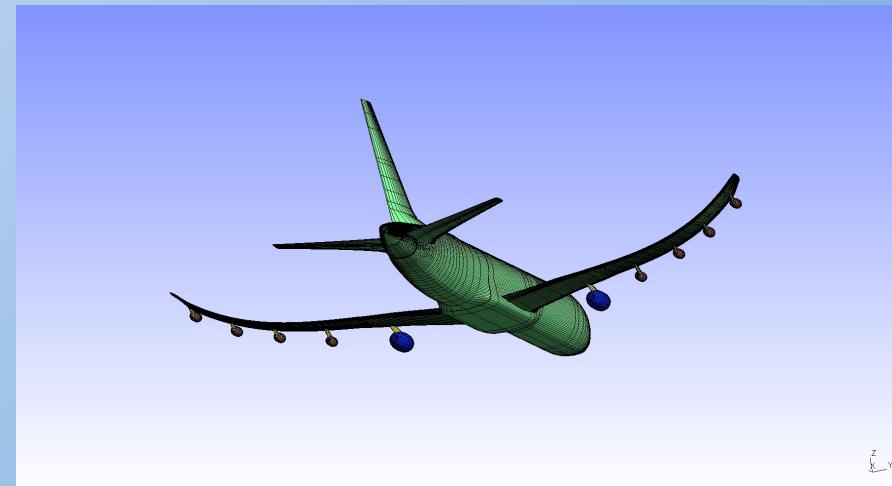
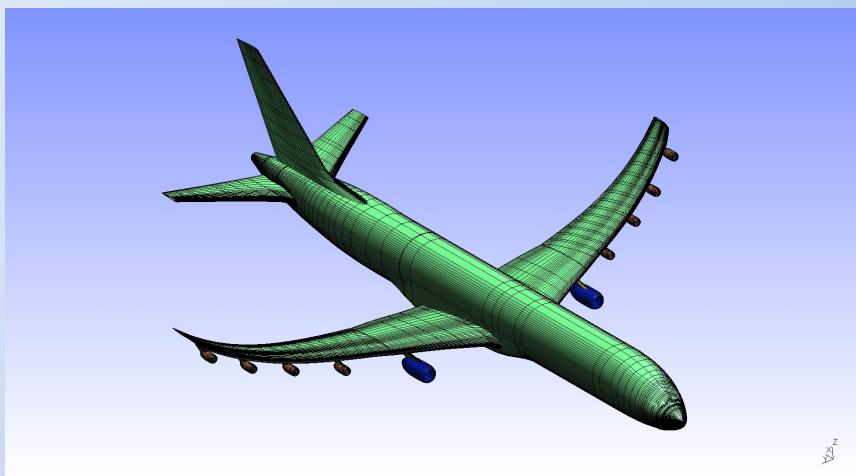
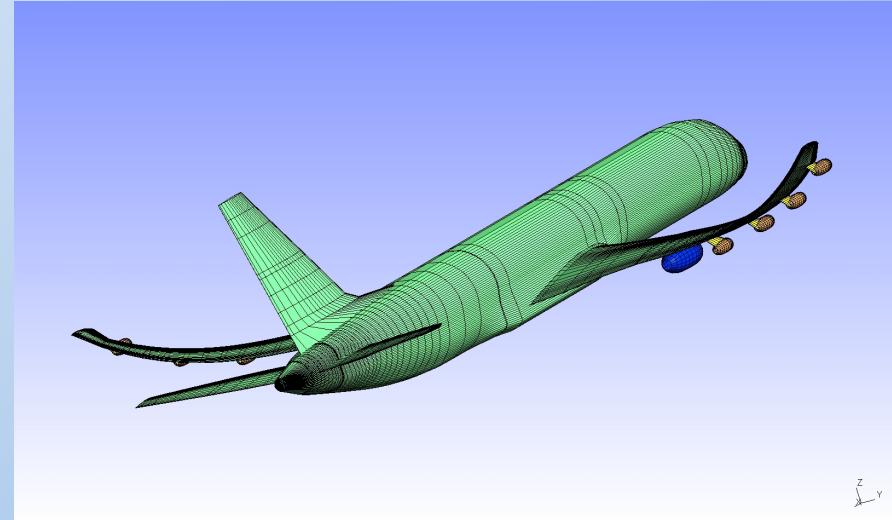
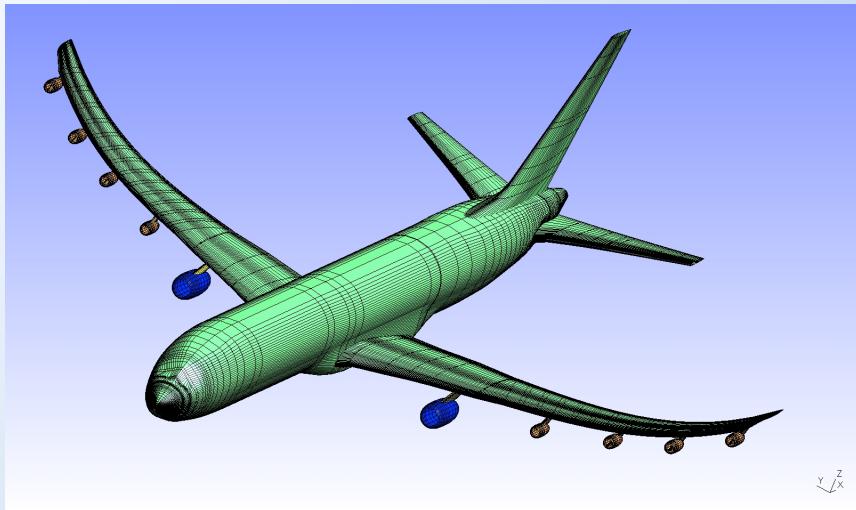
Can a synergistic fuel burn benefit be achieved over a mission profile?



# Flexible Wing Distributed Propulsion Aircraft Concept



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# Wing Shaping Using Distributed Propulsion



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## **NASA ARC/GRC Program Tasks:**

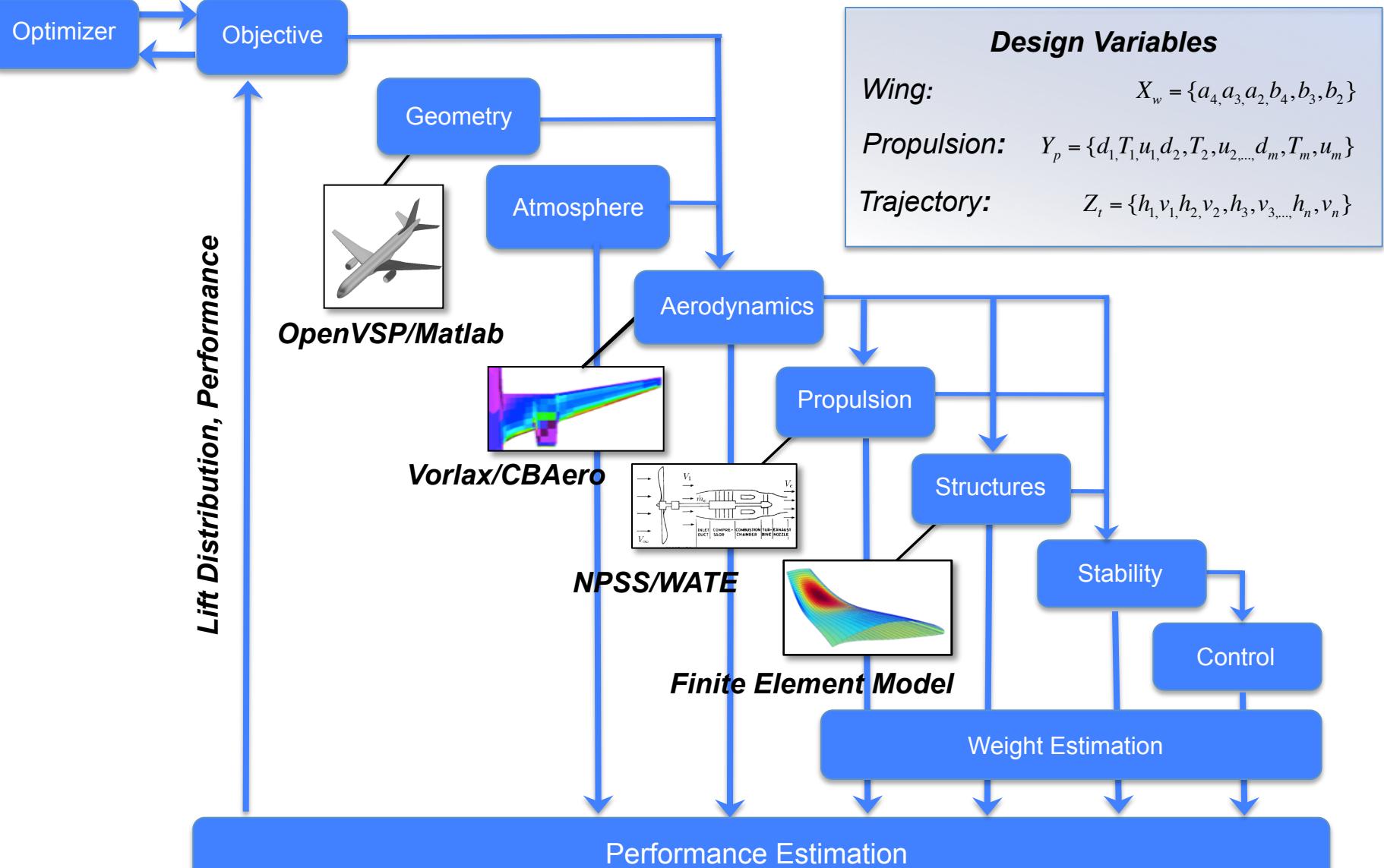
1. Distributed Propulsion Aircraft Design and Modeling
2. Wing Aeroelastic Tailoring for Optimal Spanwise L/D
3. Flutter Analysis For Determining Flight Envelope
4. Mission Performance Analysis by Trajectory Optimization

## **Boeing Program Tasks:**

1. Weight Estimation of Distributed Propulsion Components:
2. Differential Thrust in place of Rudder Control
3. Vertical Tail Sizing for Disabled Generator on One Wing
4. System Architecture and Benefits



# Multidisciplinary Design and Optimization Roadmap



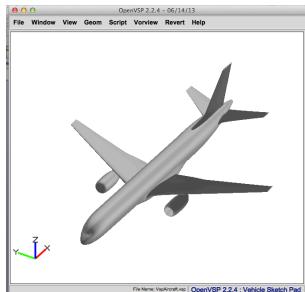


# Aerodynamic Analysis Using Vortex Lattice



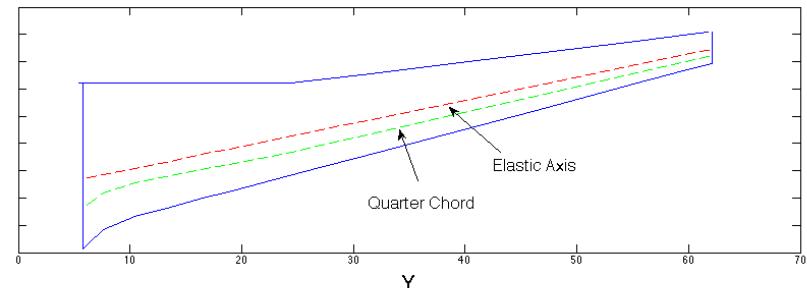
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Generic Transport Model (GTM)

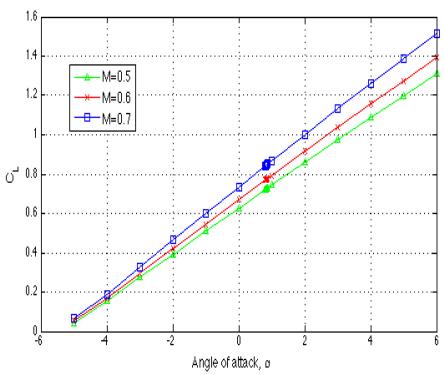


Automated Geometry Modeling Tool For  
Distributed Propulsion and Flexible Wing Aircraft

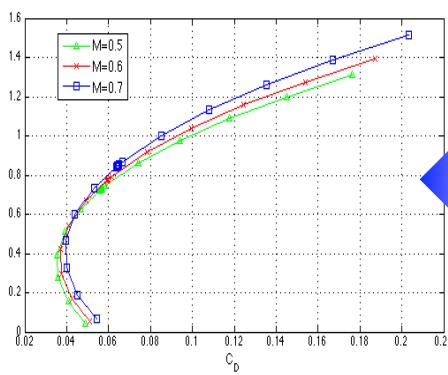
Planform Geometry



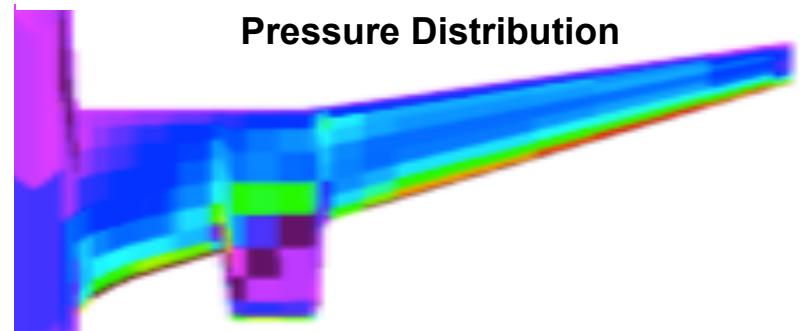
Lift Curves



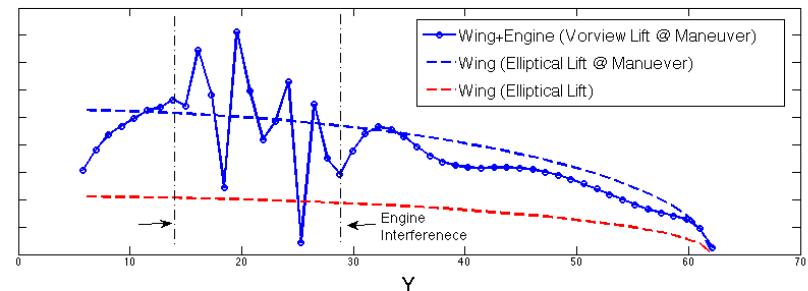
Drag Polars



Pressure Distribution



Vertical Lift Distribution



Vortex Lattice allows rapid lift curve and drag polar generation across various Mach numbers.



# Aerodynamic Analysis Using Vortex Lattice



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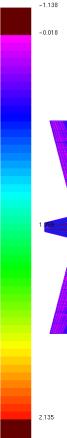
Delta Cp



Baseline GTM

MACH = 0.80  
ALPHA = 9.00  
SREF = 1951  
S0 = 0  
XBAR = 73.24  
CD,0 = 0.09727  
CM,0 = -0.05631  
CD,1 = 0.09701  
CD,T = 0.00000  
HFRS = -34

Delta Cp

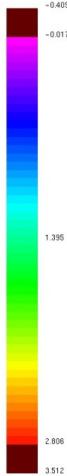


Concept 1

-3.655  
-0.358

Concept 2

Delta Cp



MACH = 0.80  
ALPHA = 9.00  
SREF = 1951  
S0 = 0  
XBAR = 16.6  
CD,0 = 0.01345  
CM,0 = -0.00200  
CD,1 = 0.47703  
CD,T = 0.00000  
CD,I = 0.08140  
HFRS = -31

Concept 3

3.213  
10.082

MACH = 0.80  
ALPHA = 9.00  
SREF = 1951  
S0 = 0  
XBAR = 16.6  
CD,0 = 0.01344  
CL = 0.52372  
CD,I = 0.08166  
CM,0 = 0.33930



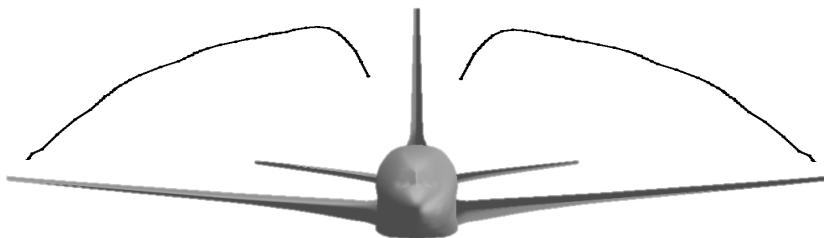
# Propulsion Interaction With Wing Aerodynamics



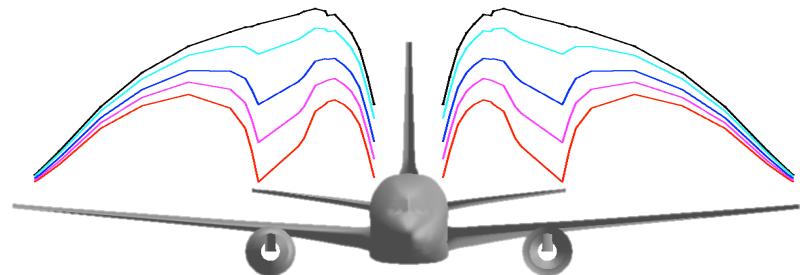
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*By adding propulsors, we introduce flow disturbances, wetted area, and viscous drag.*

Clean Wing

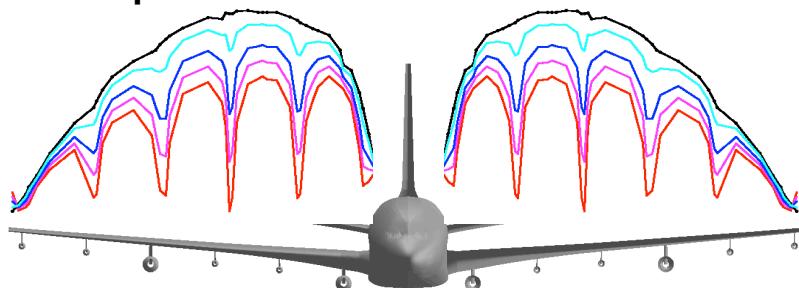


Baseline GTM

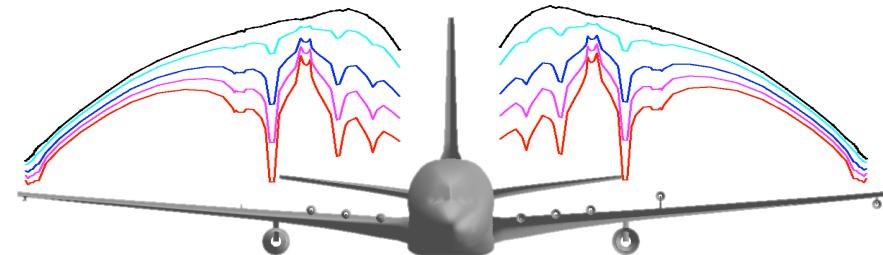


*The spanwise lift distribution is represented for design and off-design conditions.*

Concept 1



Concept 2



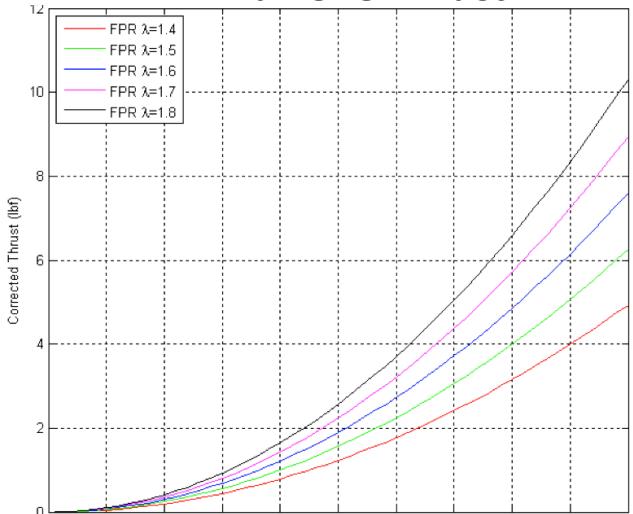
Higher fidelity tools can be used to optimize the propulsion layout and geometry.



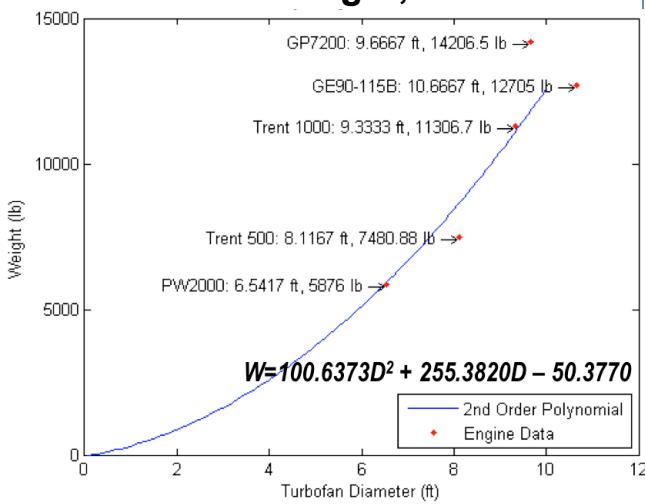
# Electric Propulsor Performance Modeling



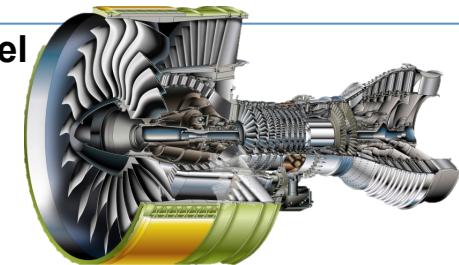
Fan SLS Thrust



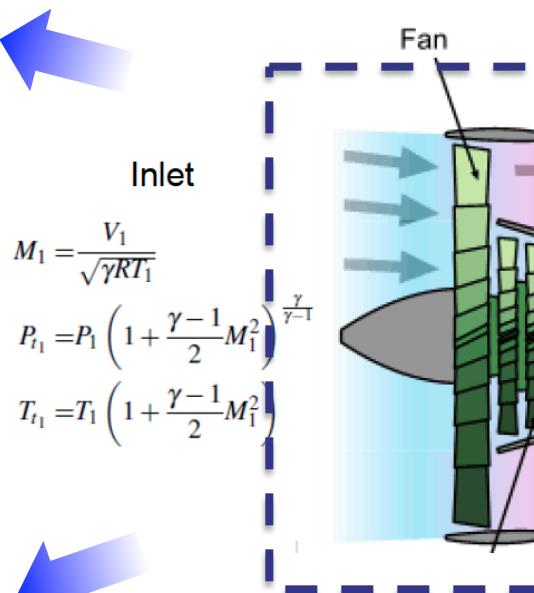
Fan Weight, FPR=1.6



NPSS/ WATE Model



Electric Propulsor Model



Electric Motor

Continuity Equation – Conservation of Mass

$$\dot{m} = \sqrt{\frac{\gamma}{RT_{t1}}} P_{t1} A M_1 \left( 1 + \frac{\gamma-1}{2} M_1^2 \right)^{-\frac{\gamma+1}{2(\gamma-1)}} = \sqrt{\frac{\gamma}{RT_{t2}}} P_{t2} A M_2 \left( 1 + \frac{\gamma-1}{2} M_2^2 \right)^{-\frac{\gamma+1}{2(\gamma-1)}}$$

An analytical model for electric propulsor performance was developed as a complement to the NPSS/WATE tools.

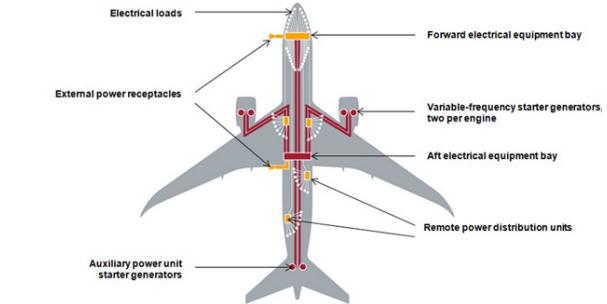


# Hybrid Electric Distributed Propulsion Modeling

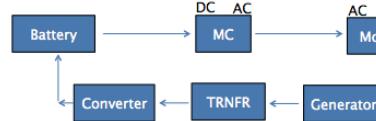


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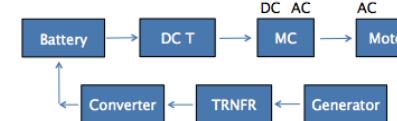
## More Electric Aircraft Design (B787)



Low voltage battery to AC motor



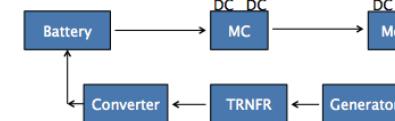
High voltage battery to AC motor



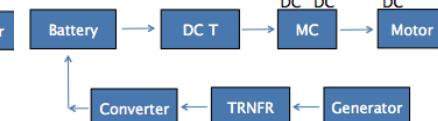
## Hybrid Electric DP Design



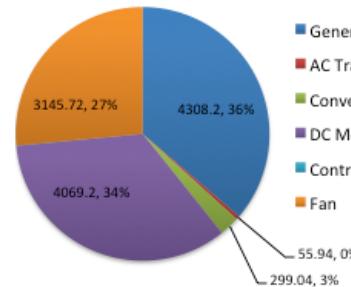
Low voltage battery to DC motor



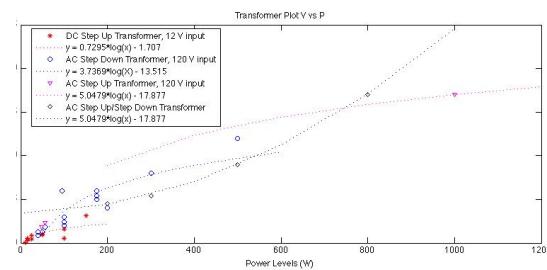
High voltage battery to DC motor



## Component Weights, lb



## Transformer Weight Trends



The selection of DC motors to produce thrust allowed battery voltages and transformer weight to be minimized.

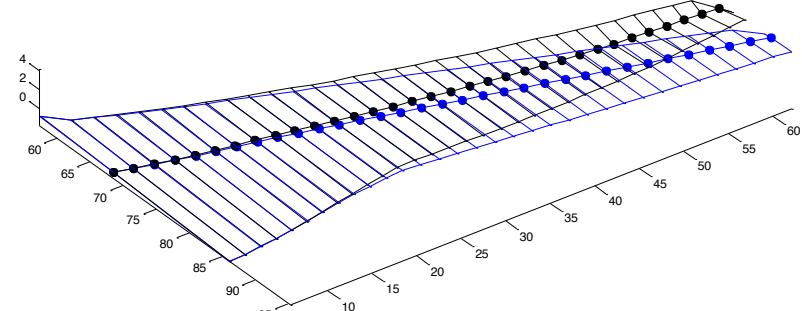
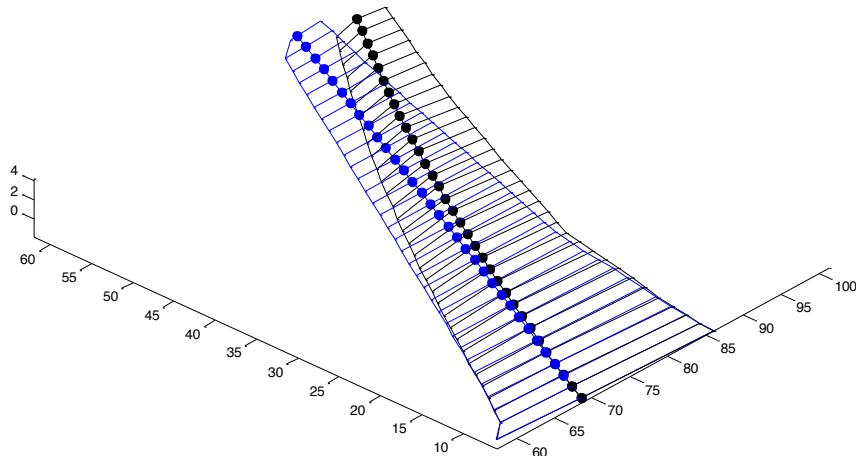


# Structural Modeling Using Finite Element Method

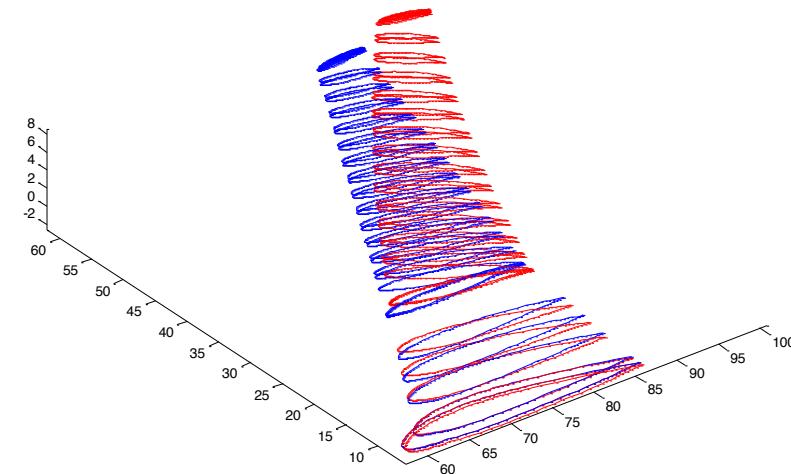
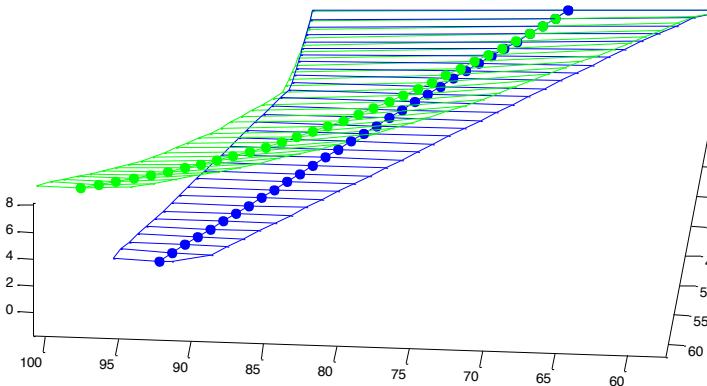


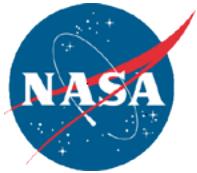
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Upgraded Finite-Element Model and Geometry Generation Tools Based in Matlab



Integrated Finite-Element Aeroelastic model for 6 degree of freedom deformation capability

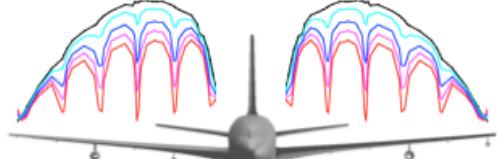




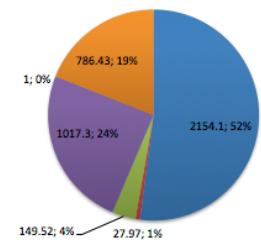
# Static Aeroelastic Modeling Tool



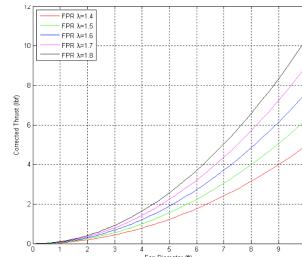
*Input Parameters (for given Mach condition):*



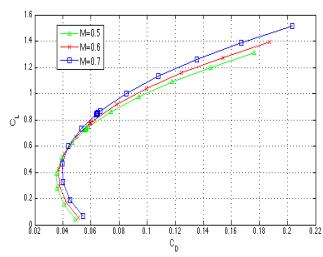
Lift Distribution



Weight Distribution

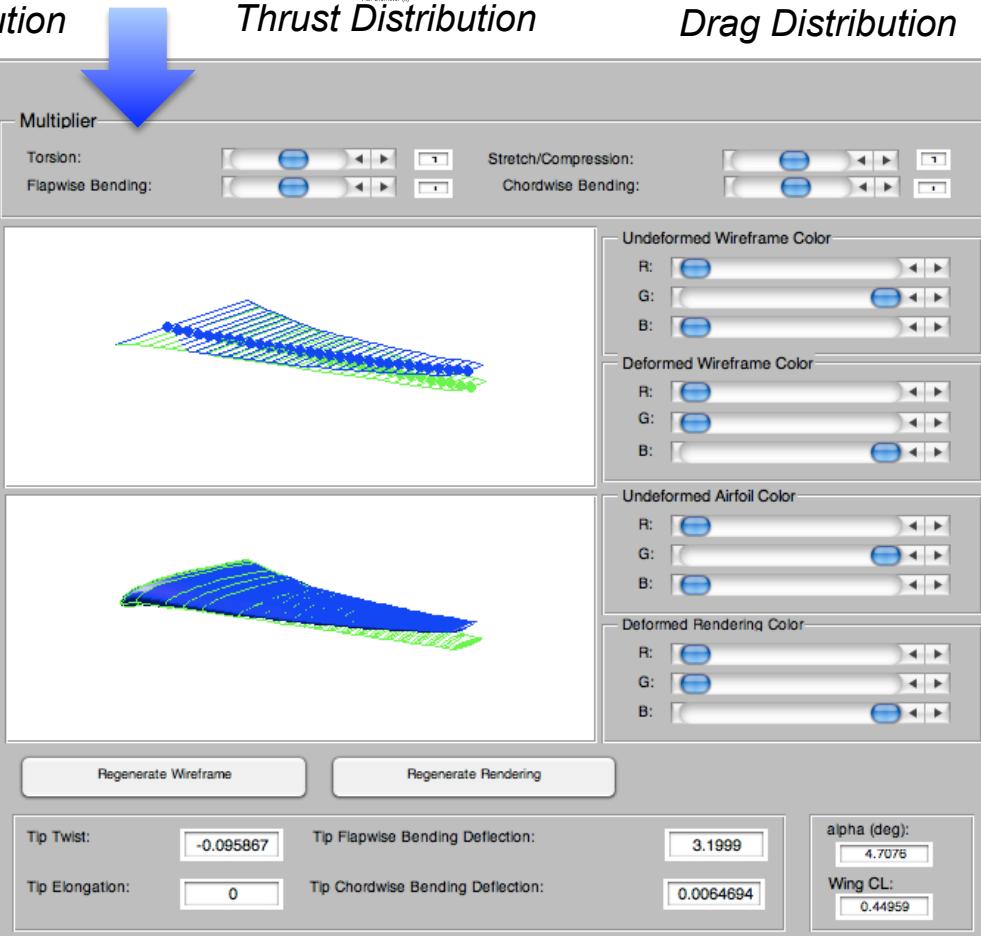
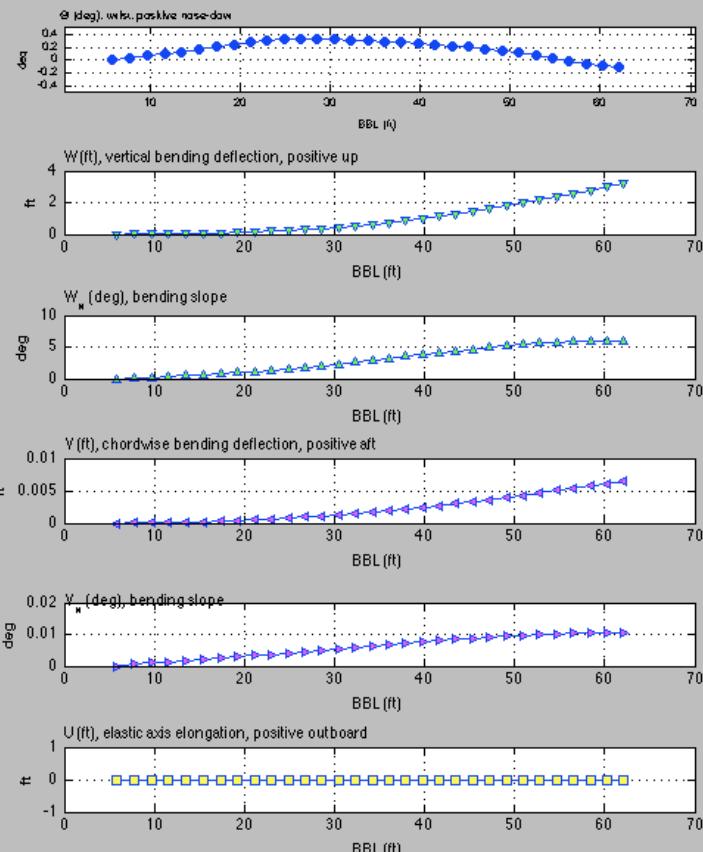


Thrust Distribution



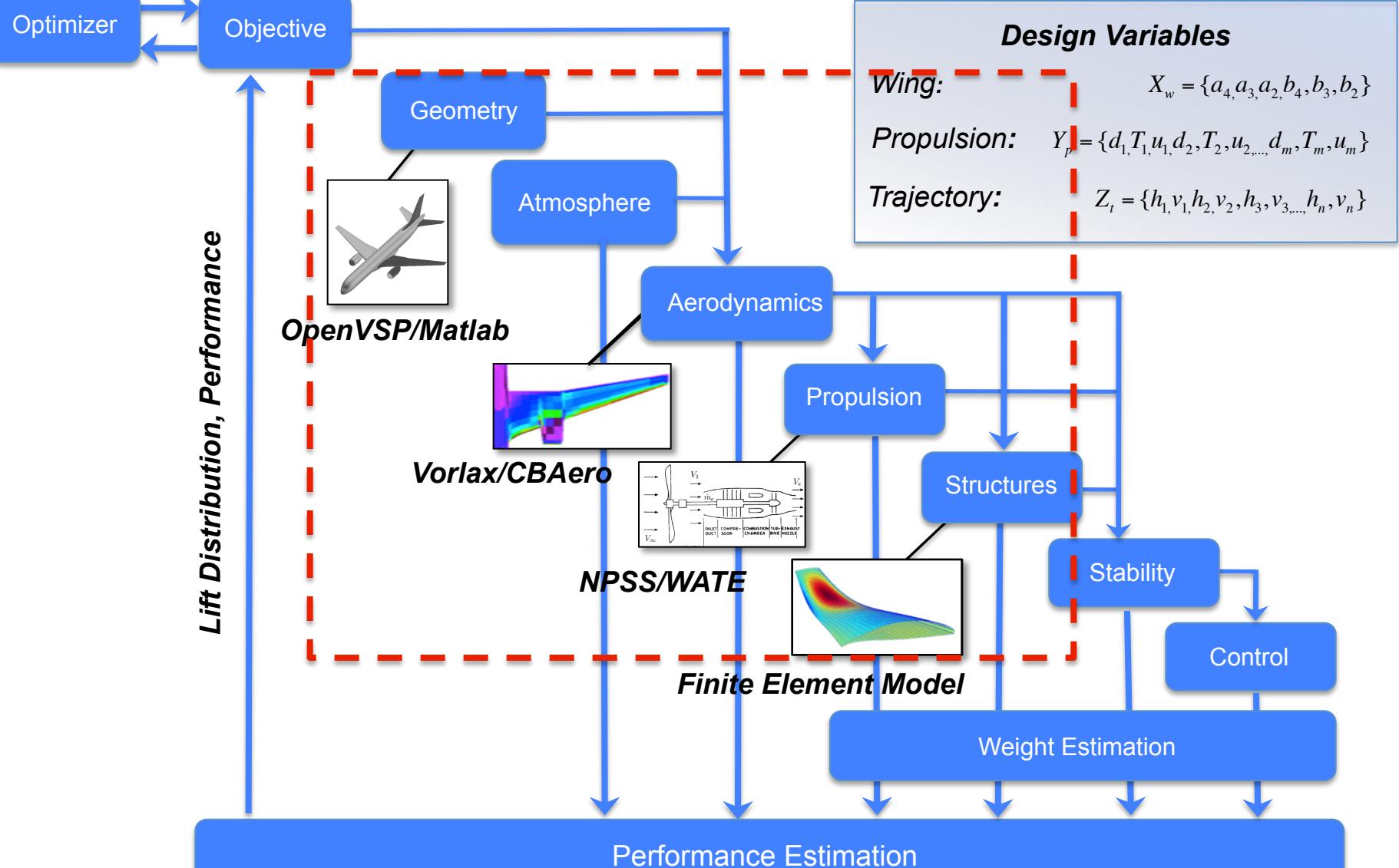
Drag Distribution

Static Deflection Results (Left Wing Analysis):





# Multidisciplinary Design and Optimization Roadmap



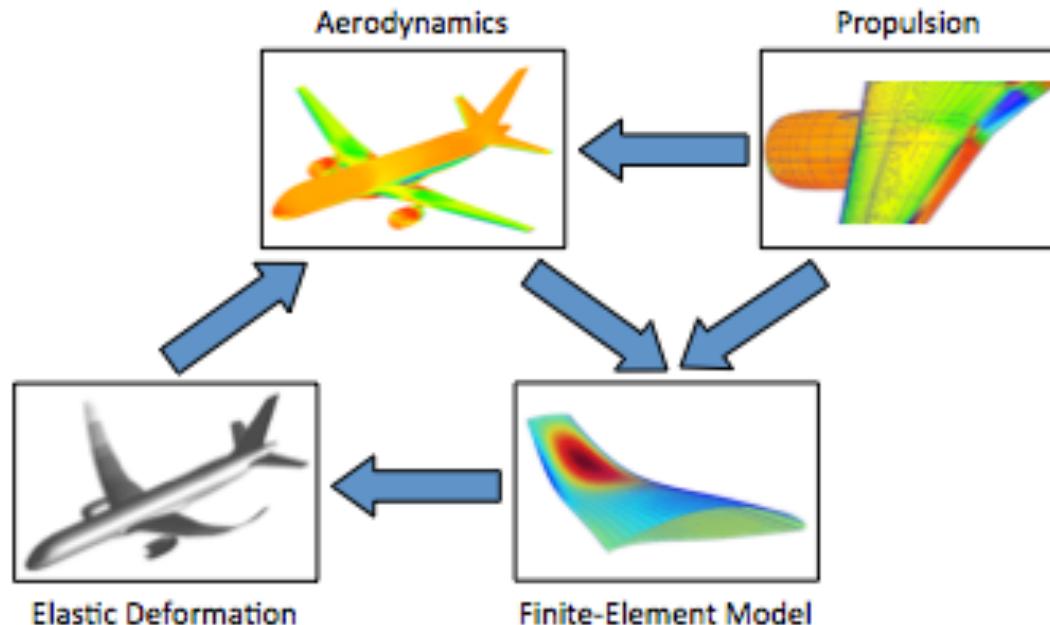


# Aero-Propulsive-Elasticity Modeling



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- Multidisciplinary Design Analysis and Optimization



- Aero-propulsive-elastic interactions

- Thrust-induced lift force

$$f_z^e = \delta(x - x_e) [(T \sin \Lambda + m_e g \Gamma) W_x + T \cos \Lambda (\Theta + \gamma) + T \sin \Lambda \Gamma - m_e g]$$

- Thrust-induced elastic deformation
  - Thrust-induced angle of attack

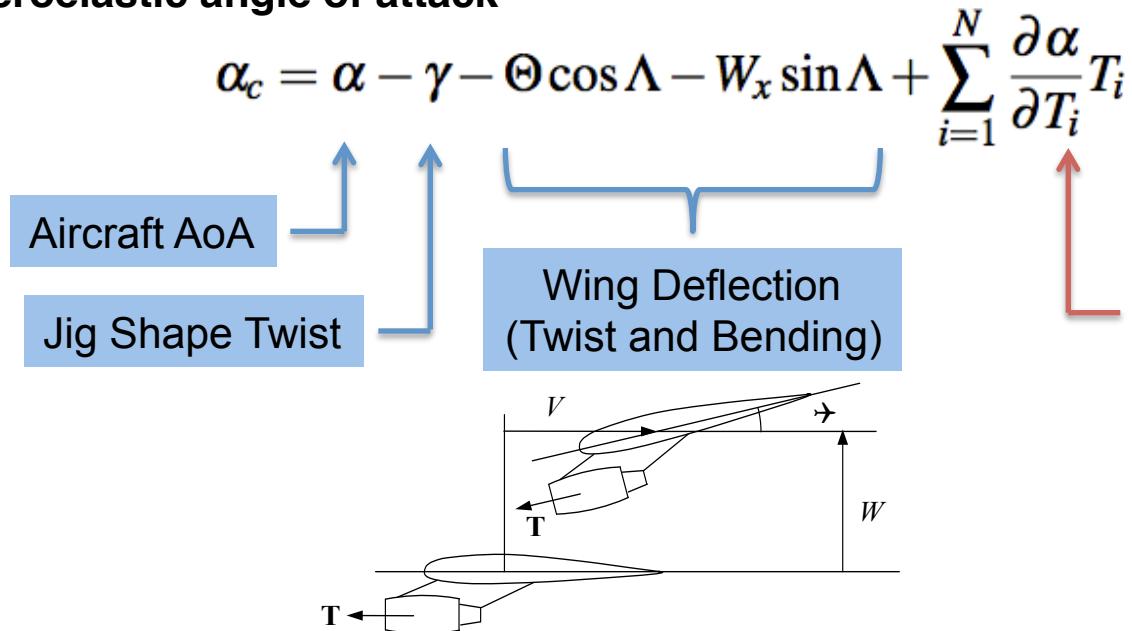


# Distributed Propulsion Wing Shaping Control



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- Local aeroelastic angle of attack



- Spanwise lift can be tailored by aeroelastic deflections created by distributed propulsion

$$\Theta(x) = \Psi(x) K_\theta^{-1} \left( F_{\theta_0} + F_{\theta_\alpha} \alpha + \sum_{i=1}^N F_{\theta_{T_i}} T_i \right)$$

$$W(x) = \Phi(x) K_w^{-1} \left( F_{w_0} + F_{w_\alpha} \alpha + \sum_{i=1}^N F_{w_{T_i}} T_i \right)$$



# Thrust-Induced Lift

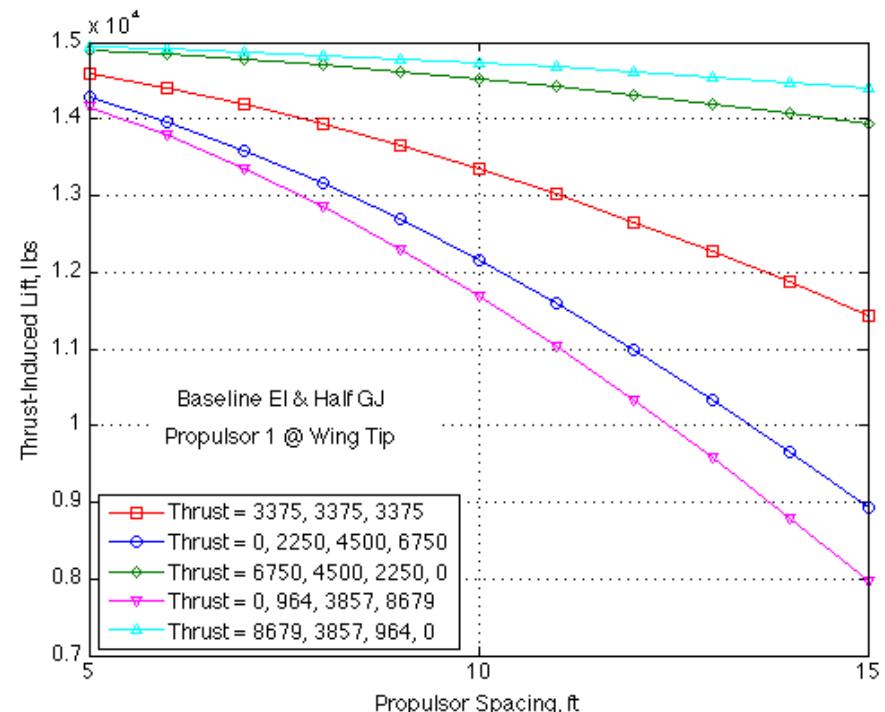
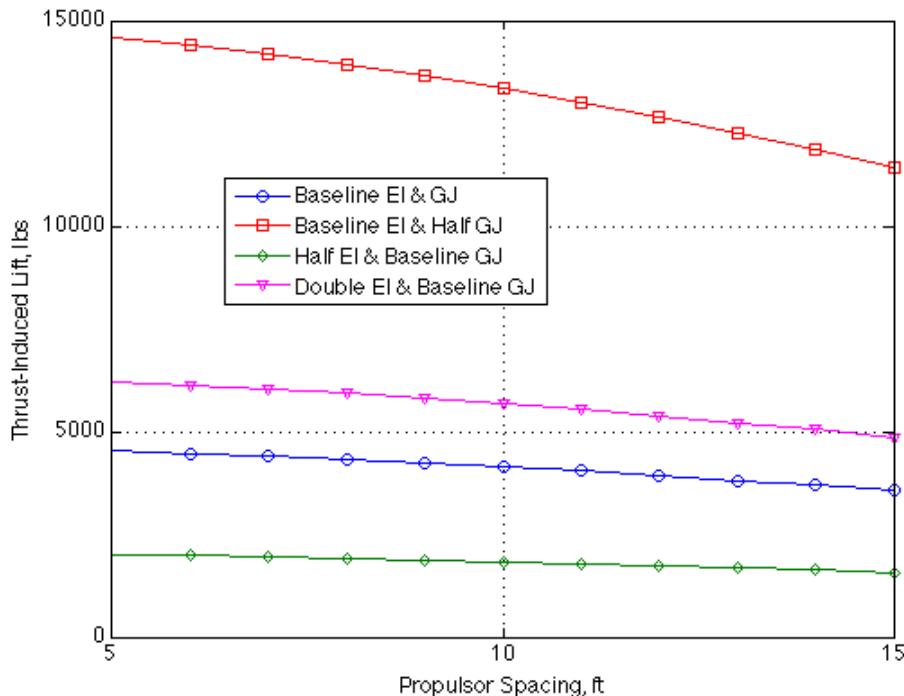


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## Sensitivity of thrust-induced lift with propulsor spacing for

- Reduced bending ( $EI$ ) and torsional stiffness ( $GJ$ )
- Uniformly spaced propulsors inboard from wingtip
- Distributed thrust along wingspan

$$C_L = C_{L_0} + C_{L\alpha} \alpha + \sum_i^N C_{LT_i} T_i$$



Thrust-induced lift is sensitive to torsional stiffness (GJ) and placement near the wingtip.

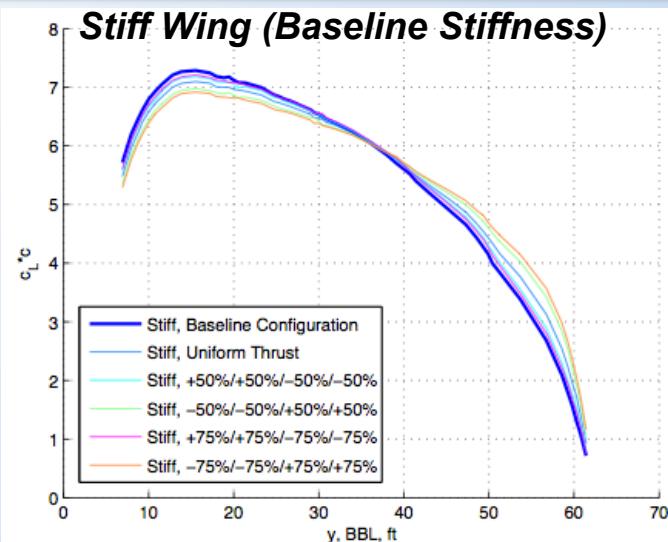


# Effect of Wing Stiffness on Spanwise L/D

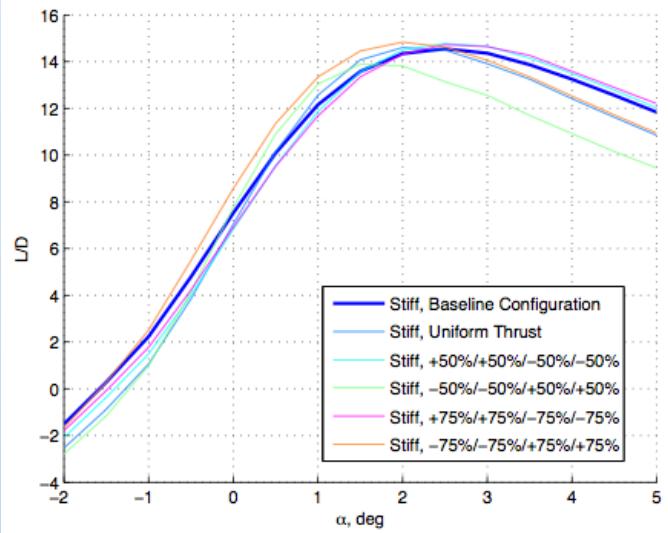


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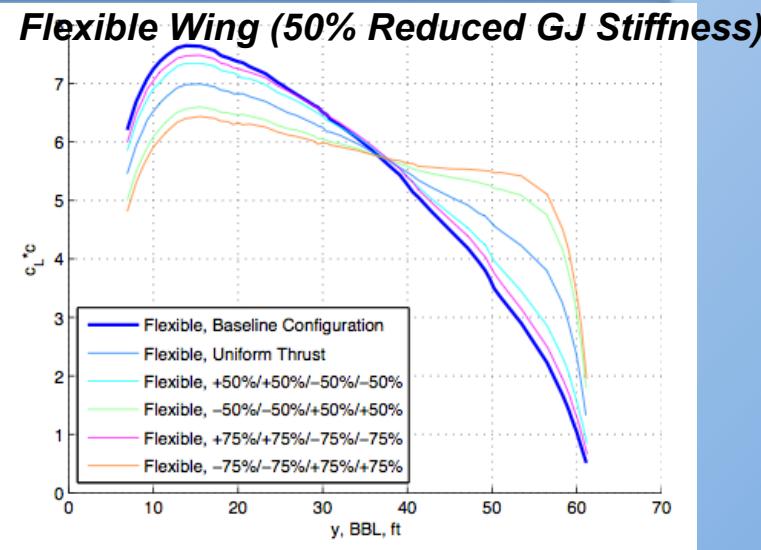
Lift Distribution



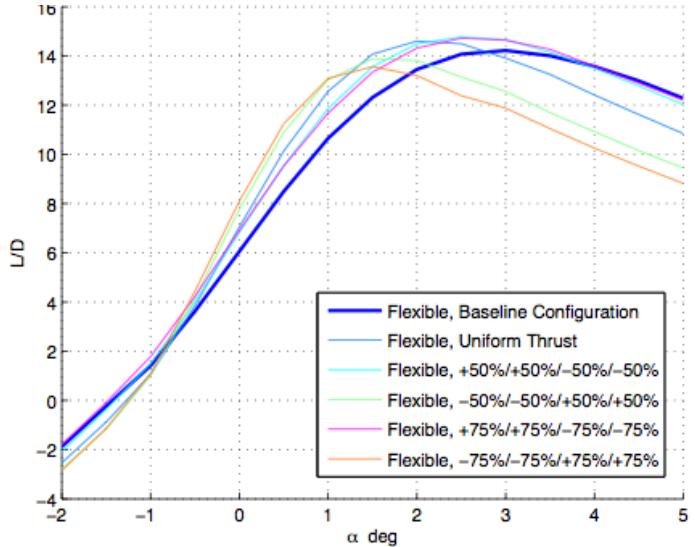
Aerodynamic Efficiency



Lift Distribution



Aerodynamic Efficiency



Aerodynamic efficiency is sensitive to wing bending/torsional stiffness and local propulsive forces/momenta.



# Relative Improvement of L/D Over Baseline



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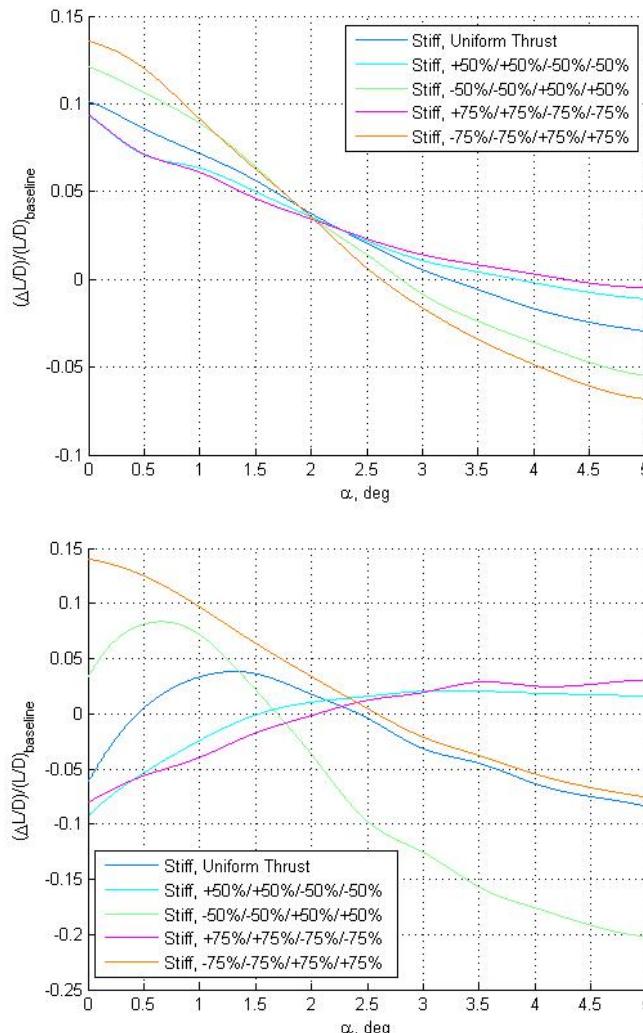


1 Generator,  
4 Fans Per Wing

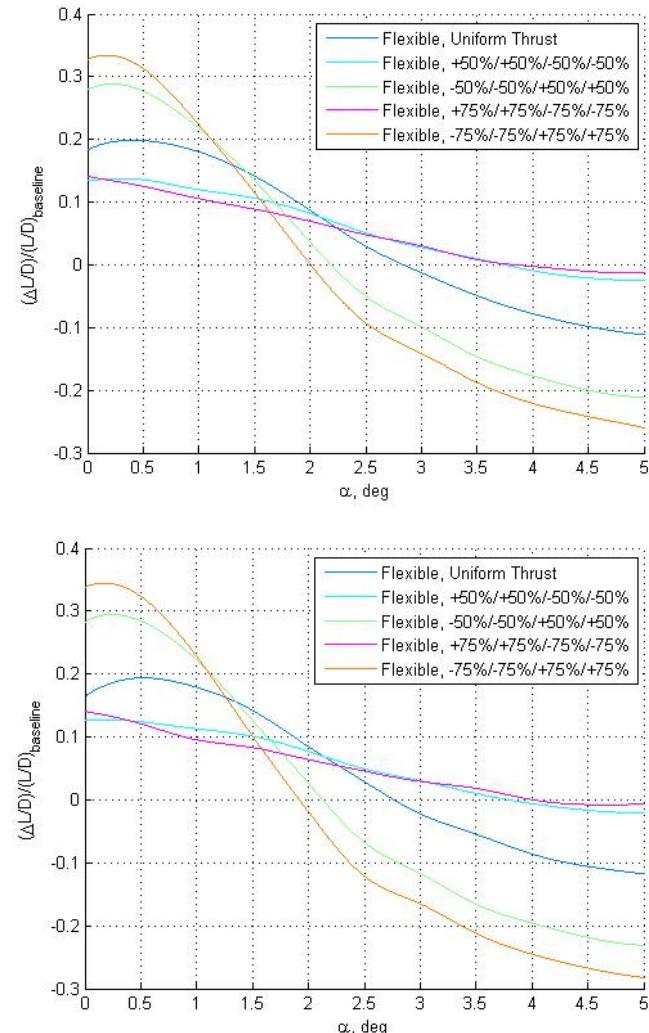


2 Generators  
4 Fans Per Wing

*Stiff Wing (Baseline Stiffness)*



*Flexible Wing (50% Reduced GJ Stiffness)*





# Trajectory Optimization

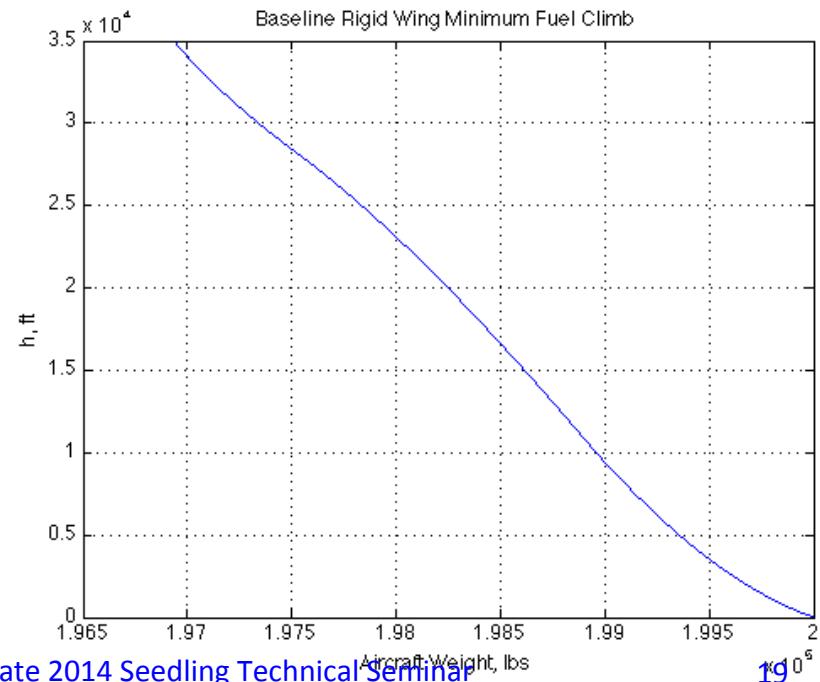
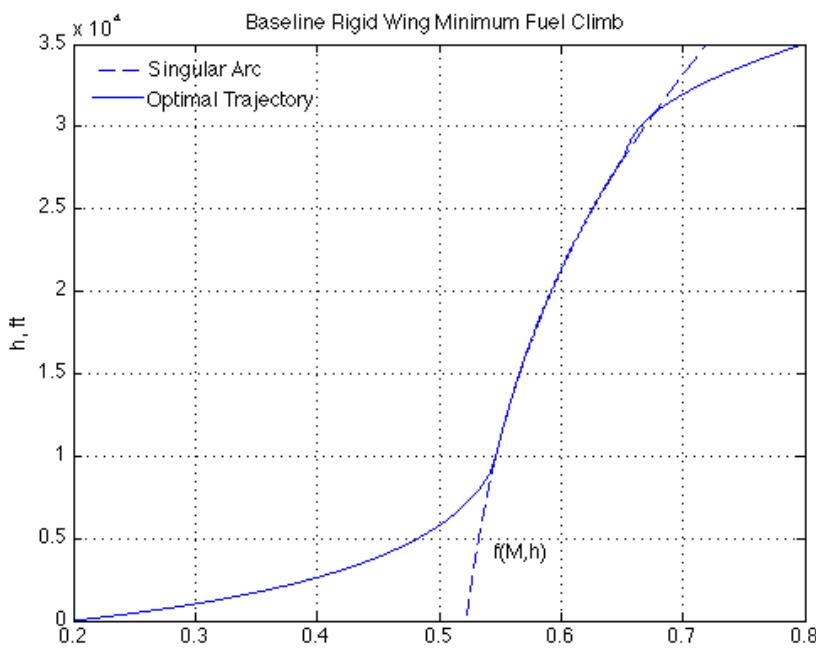


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- **Mission profile consists of climb, cruise, and continuous descent**
  - Based on Operational Empty Weight of 175,000 carrying 75,000 lb fuel
- **Minimum fuel climb**
  - Maximum thrust climb along optimal singular arc

$$f(V, h) = F + V \frac{\partial F}{\partial V} - \frac{V^2}{g} \frac{\partial F}{\partial h} - \frac{FV}{cT} \left[ \frac{\partial (cT)}{\partial V} - \frac{V}{g} \frac{\partial (cT)}{\partial h} \right] = 0 \quad F = \frac{T - D}{W}$$

- Baseline aircraft burns about 3,100 lbs in climb
- Descent approximated as optimal climb with the same negative excess thrust





# Cruise Analysis



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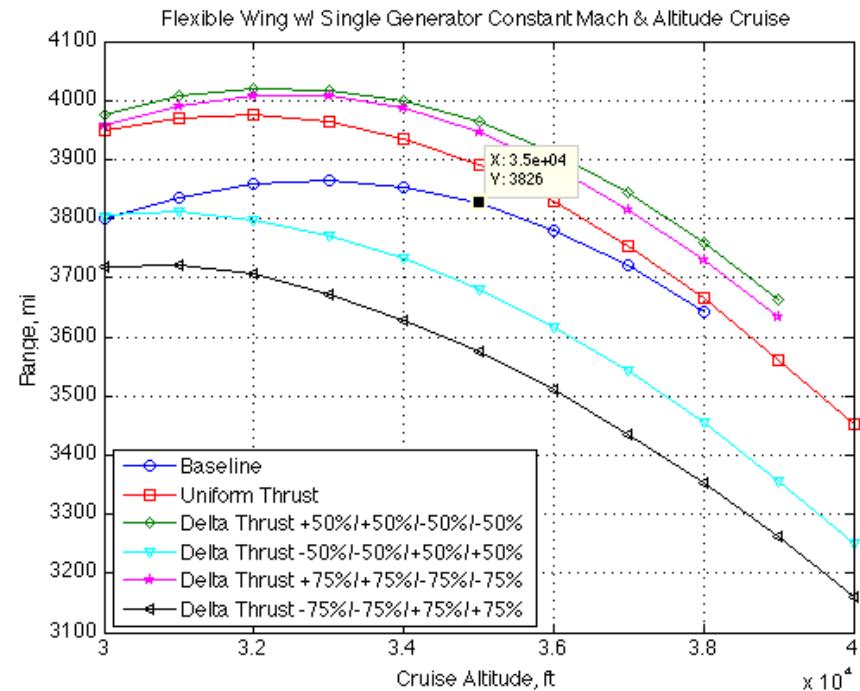
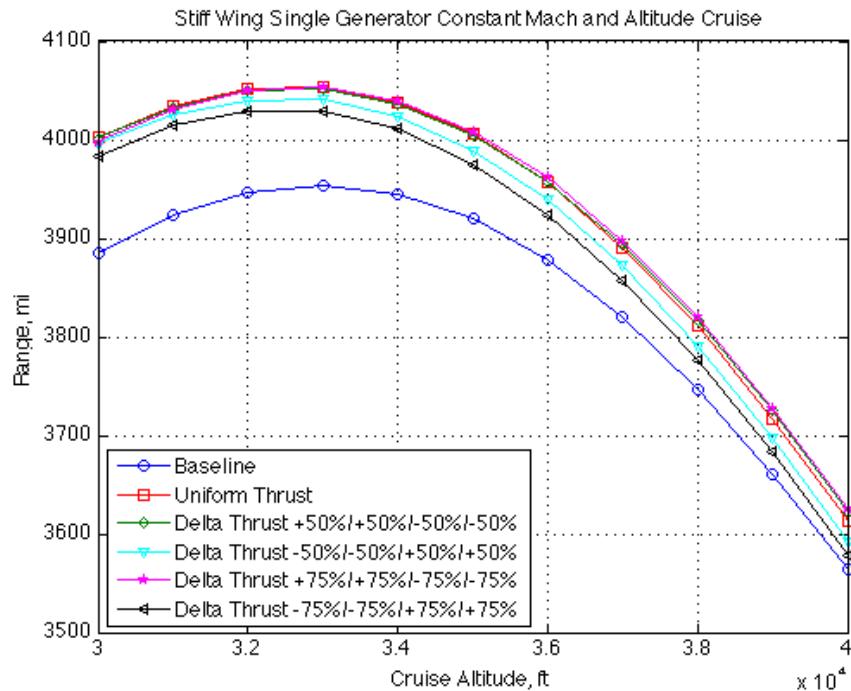
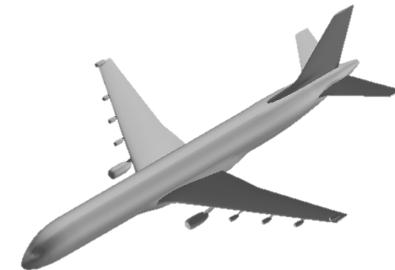
- **Two types of cruise**

- Constant Mach and constant altitude
- Constant Mach and constant angle of attack at maximum L/D
- Breguet's range equation

$$r = - \int_{W_i}^{W_f} \frac{V}{c} \left( \frac{L}{D} \right) \frac{dW}{W}$$

- specific thrust fuel consumption for turbofan engines

$$c = (0.2921M + 0.2092) \sqrt{\theta(h) \left( 1 + \frac{\gamma-1}{2} M^2 \right)}$$





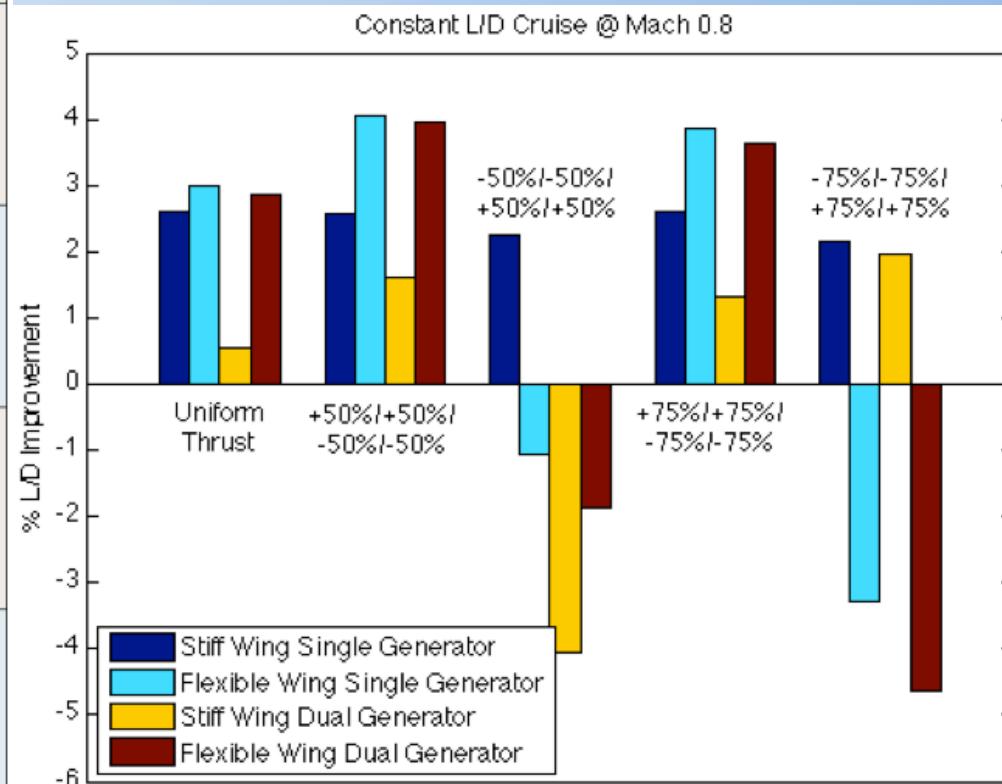
# L/D Improvement Results



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- L/D improvement by single and dual generator configurations**

Wing	Generator	Thrust	Range, mi	% L/D Increase
Stiff	Single	Baseline	3980	0.00
Stiff	Single	Uniform	4084	2.61
Stiff	Single	+50%/-50%/-50%/-50%	4082	2.57
Stiff	Single	-50%/-50%/+50%/+50%	4070	2.26
Stiff	Single	+75%/-75%/-75%/-75%	4083	2.59
Stiff	Single	-75%/-75%/+75%/+75%	4065	2.15
Flexible	Single	Baseline	3891	0.00
Flexible	Single	Uniform	4007	2.99
Flexible	Single	+50%/-50%/-50%/-50%	4048	4.04
Flexible	Single	-50%/-50%/+50%/+50%	3850	-1.05
Flexible	Single	+75%/-75%/-75%/-75%	4041	3.87
Flexible	Single	-75%/-75%/+75%/+75%	3763	-3.29
Stiff	Dual	Baseline	3980	0.00
Stiff	Dual	Uniform	4002	0.55
Stiff	Dual	+50%/-50%/-50%/-50%	4044	1.62
Stiff	Dual	-50%/-50%/+50%/+50%	3818	-4.07
Stiff	Dual	+75%/-75%/-75%/-75%	4032	1.32
Stiff	Dual	-75%/-75%/+75%/+75%	4058	1.97
Flexible	Dual	Baseline	3891	0.00
Flexible	Dual	Uniform	4002	2.85
Flexible	Dual	+50%/-50%/-50%/-50%	4044	3.95
Flexible	Dual	-50%/-50%/+50%/+50%	3818	-1.88
Flexible	Dual	+75%/-75%/-75%/-75%	4032	3.63
Flexible	Dual	-75%/-75%/+75%/+75%	3711	-4.62



Cruise Range for 75,000 lbs Fuel Burn

Varying the distribution of thrust along a flexible wing could potentially result in 4% improvement in L/D

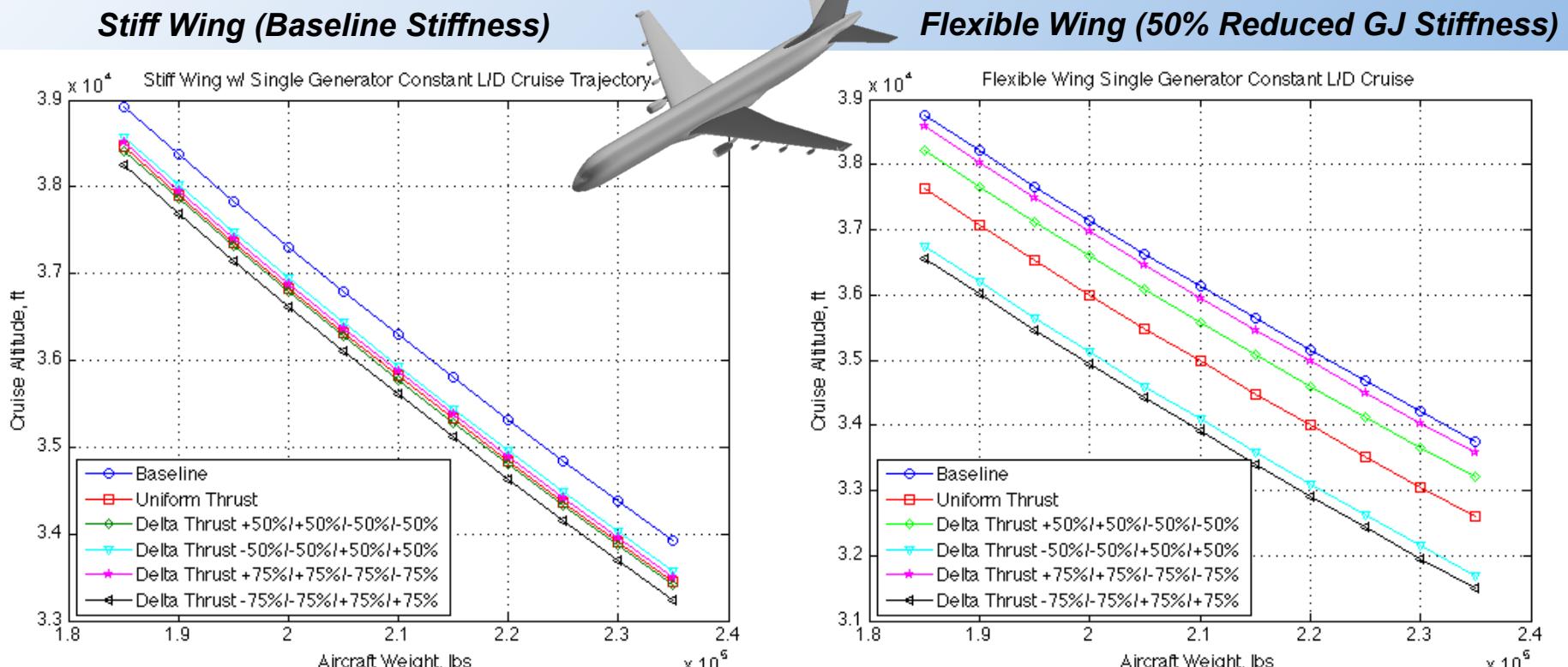


# Maximum L/D Cruise Trajectories



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- Climb cruise altitude as function of aircraft weight for single generator



Distributing thrust along a flexible wing enable new optimal cruise flight trajectories



# Flutter Analysis With Distributed Propulsion



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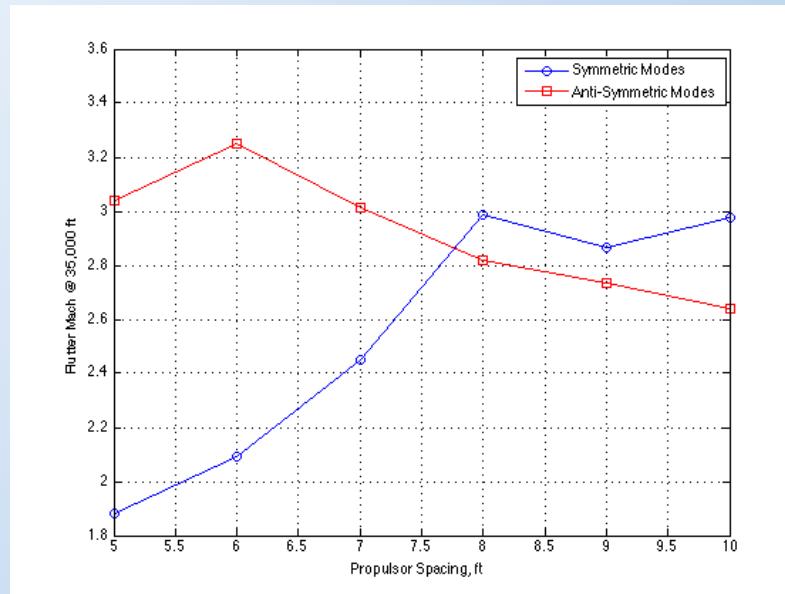
## Sensitivity of flutter speed with propulsor placement

### DP Aircraft Description

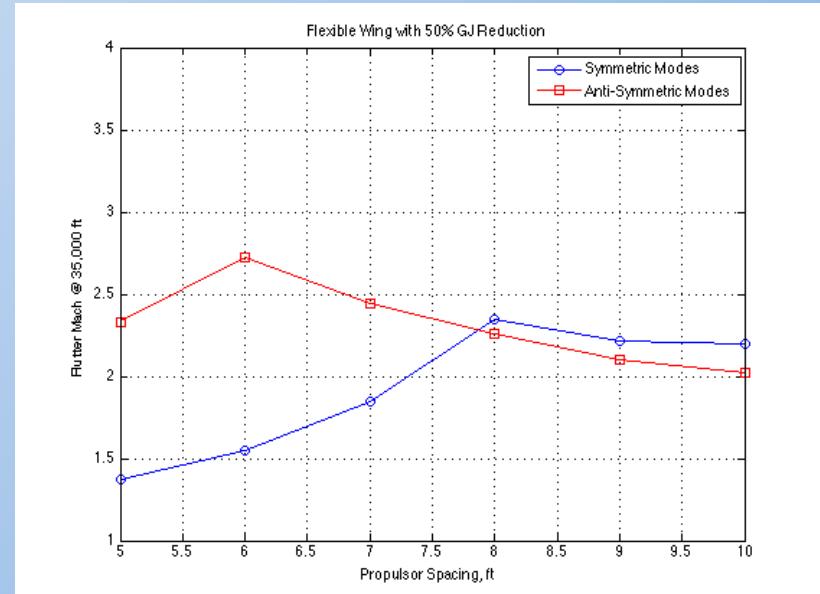
1 Generator Near Wing Root, 4 Fans Outboard  
Fans equally spaced inboard from wingtip



### Stiff Wing (Baseline Stiffness)



### Flexible Wing (50% Reduced GJ Stiffness)



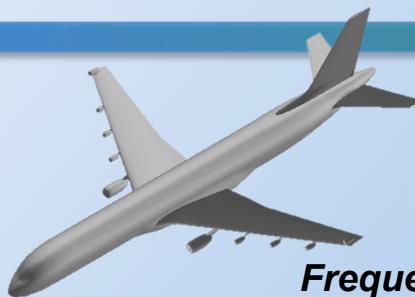
Initial analysis concluded that flutter is not an issue (for this configuration)



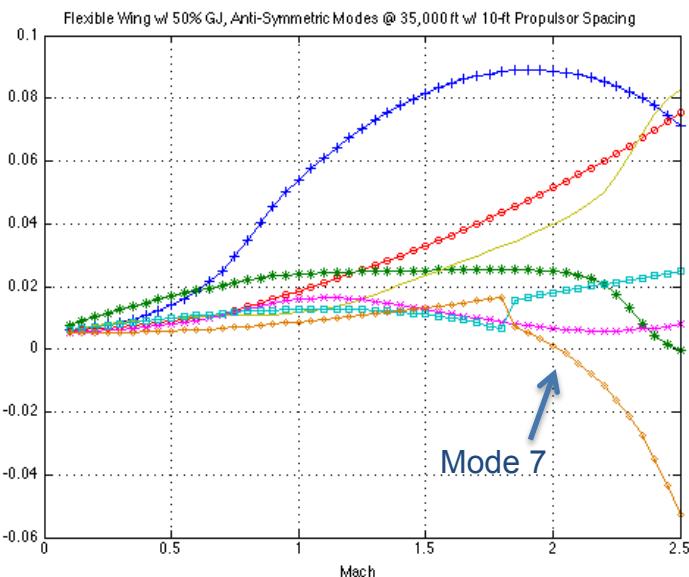
# Flutter Analysis With Distributed Propulsion



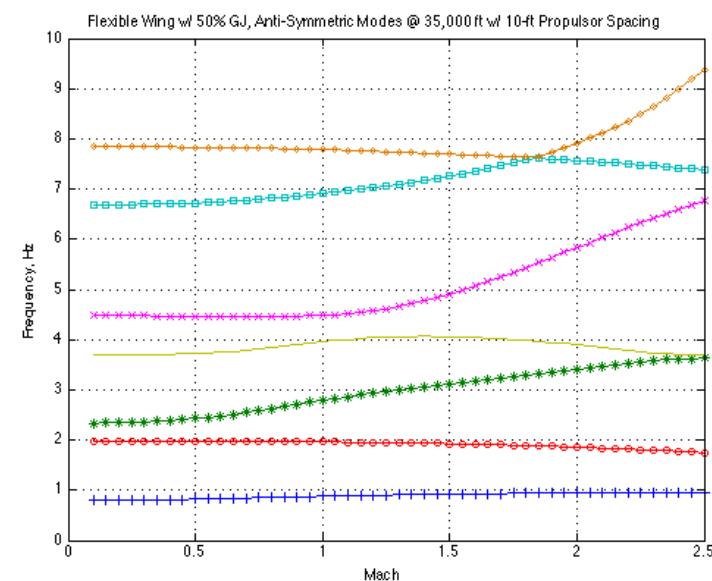
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## Damping Response



## Frequency Response



Initial analysis concluded that flutter is not an issue (for this configuration)

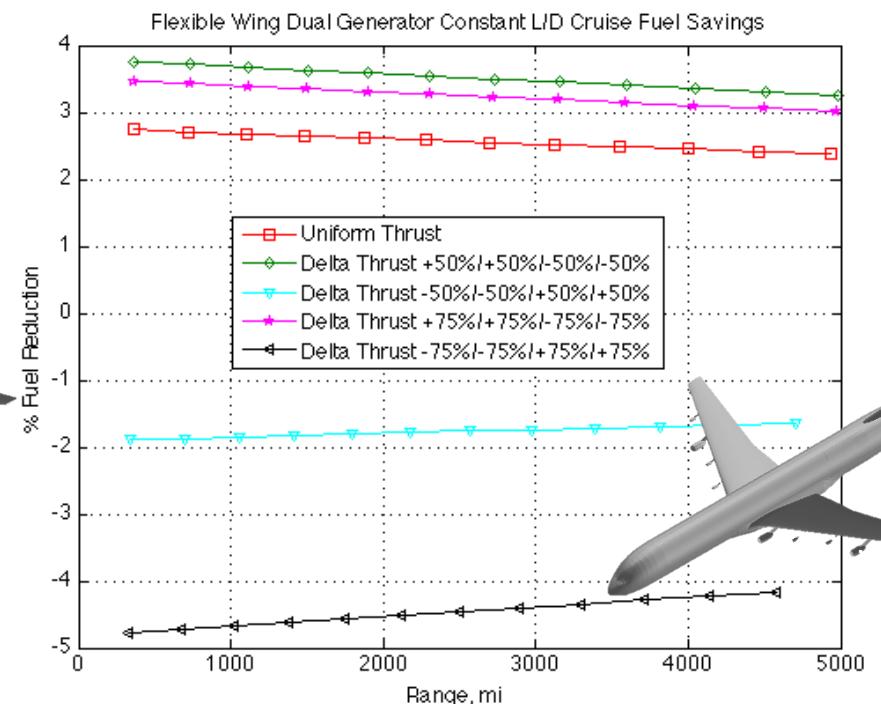
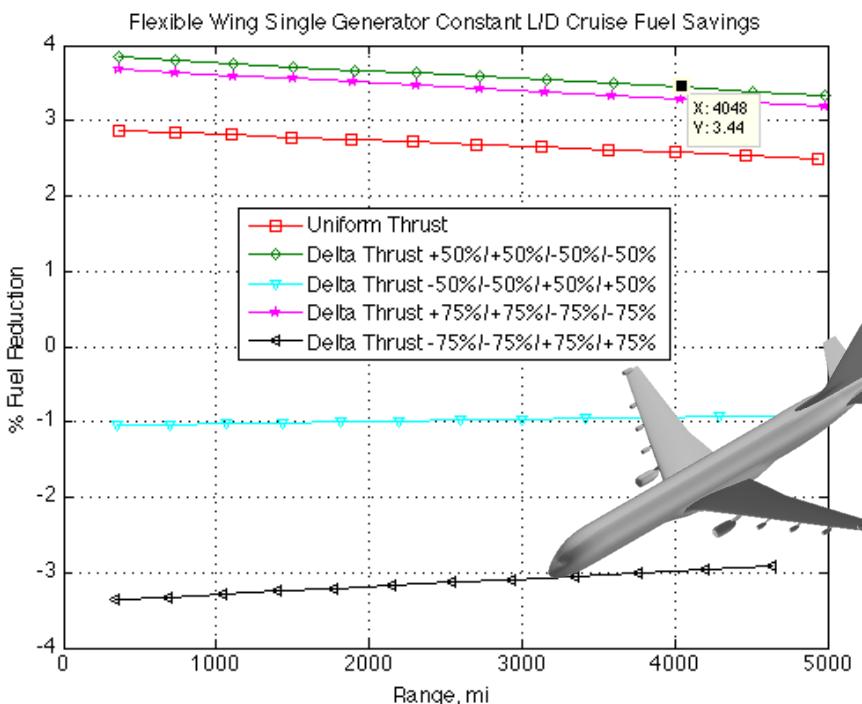


# Fuel Reduction Opportunities



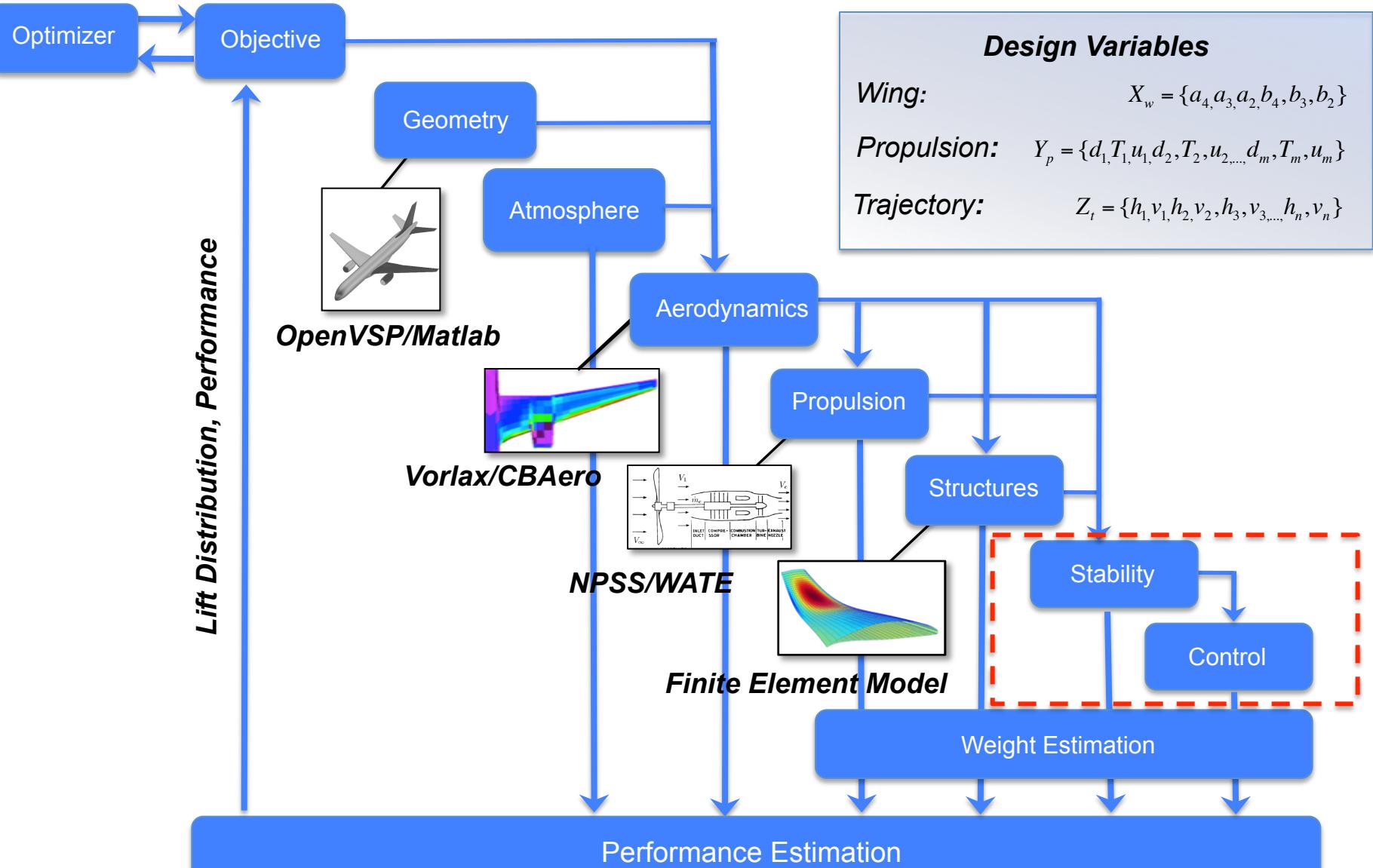
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- Single generator is slightly more efficient
- Increasing thrust of inboard propulsors achieves better L/D
- Distributed propulsion could achieve almost 4% fuel reduction with flexible wing





# Multidisciplinary Design and Optimization Roadmap





# System Architecture – Benefits and Constraints



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## Architecture:

- 4 electric engines on each wing
- Engines on each wing linked to dual turbo generators
- Flight control commands separate to each of the electric engines

## Benefits:

- Use different thrust commands to each of the four engines to twist the wing, improves lift to drag ratio; results in fuel savings
- Separate thrust commands to each engine can steer and stabilize the aircraft
- Multiple engines: can fail with little effect on flight path
- Engines can be control effectors, minimize flight control cost

## Constraints:

- Dual turbo generators power the four engines on the same wing
- Acceleration and rate limiting on the electric engines

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# GTM Model with Four Engines per Wing



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## Objectives and Purpose

- (i) Using GTM Model to evaluate differential engine thrust for enhanced directional stability
- (ii) Use GTM Model to analyze rudder sizing requirements

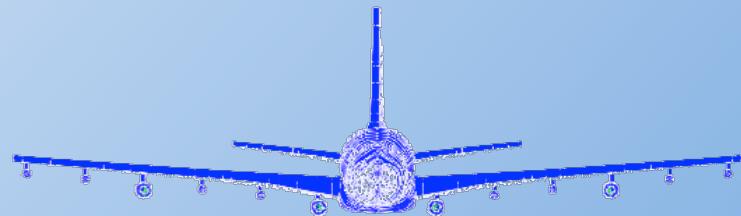
## GTM Engine Dynamics (Second Order)

$$\zeta_{\text{engine}} = 0.8; \\ \omega_{\text{engine}} = 0.3571;$$

## Flight Conditions

Mach 0.8, Alt=15000ft (Differential Thrust Control Study)

Mach 0.28, Alt=20ft (Rudder Sizing Study)



*Notional DP Aircraft Geometry*

Engines are numbered from the wing root outward:

Elastic Axis CG location of each engine:

Total max thrust per wing = 44042lb

Total max thrust per engine = 44042lb/4=11010.5 lb

Engine 1 (E1):  $y=20\text{ft}$

Engine 2 (E2):  $y=30\text{ft}$

Engine 3 (E3):  $y=50\text{ft}$

Engine 4 (E4):  $y=60\text{ft}$

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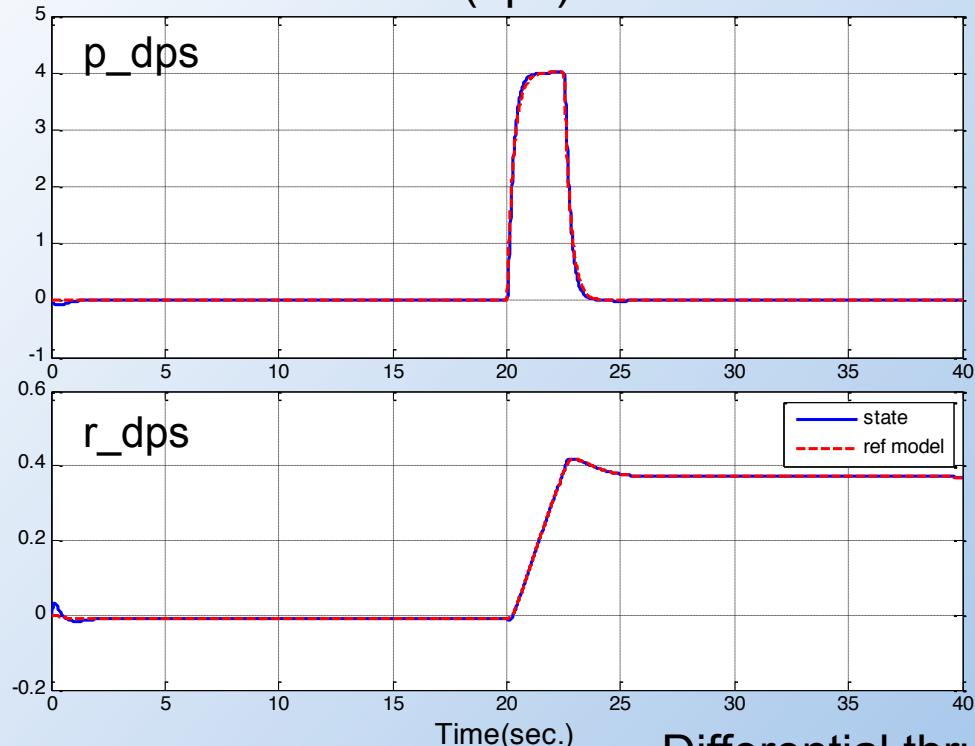
# Differential Thrust Controller Nominal

Mach= 0.8, Alt=15000 ft

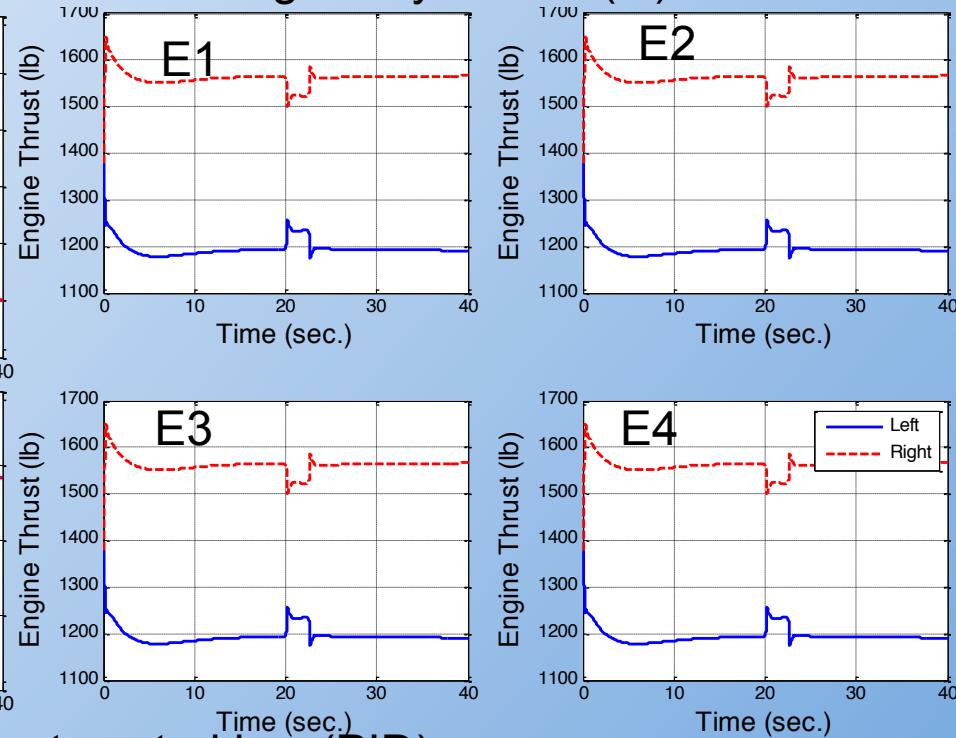


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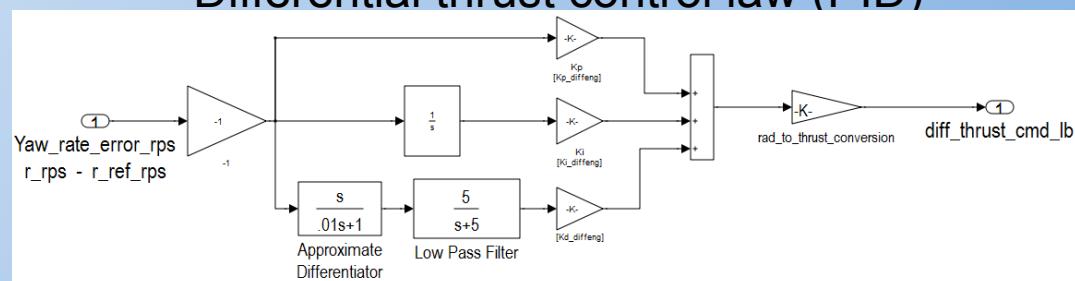
Rates (dps)



Engine Dynamics (lb)



Differential thrust control law (PID)



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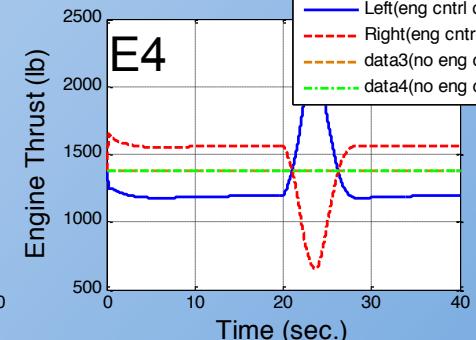
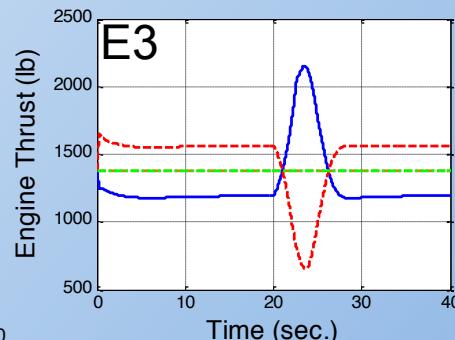
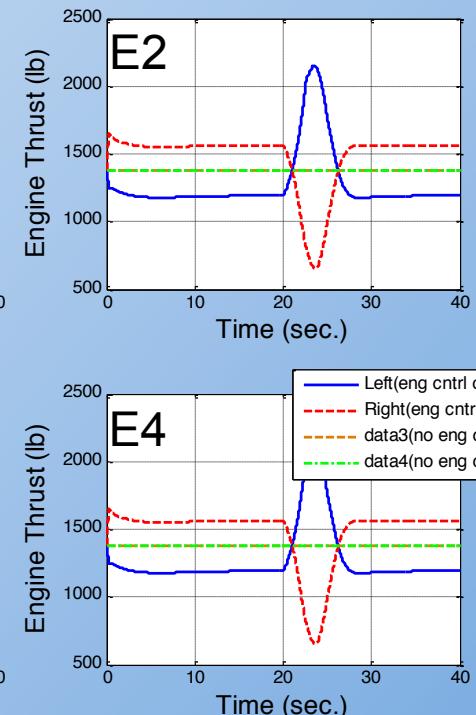
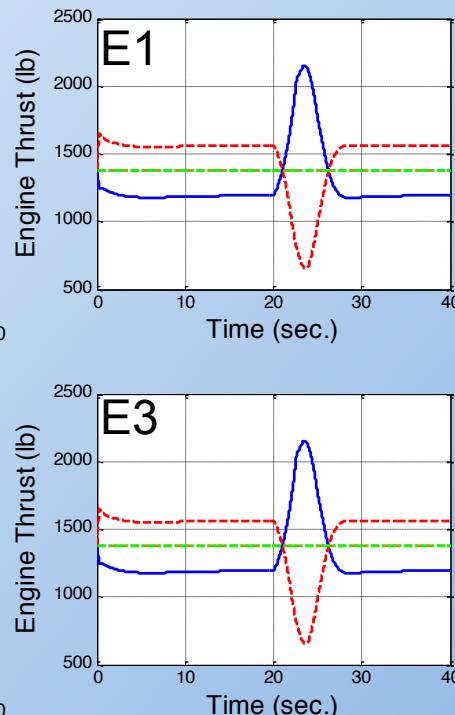
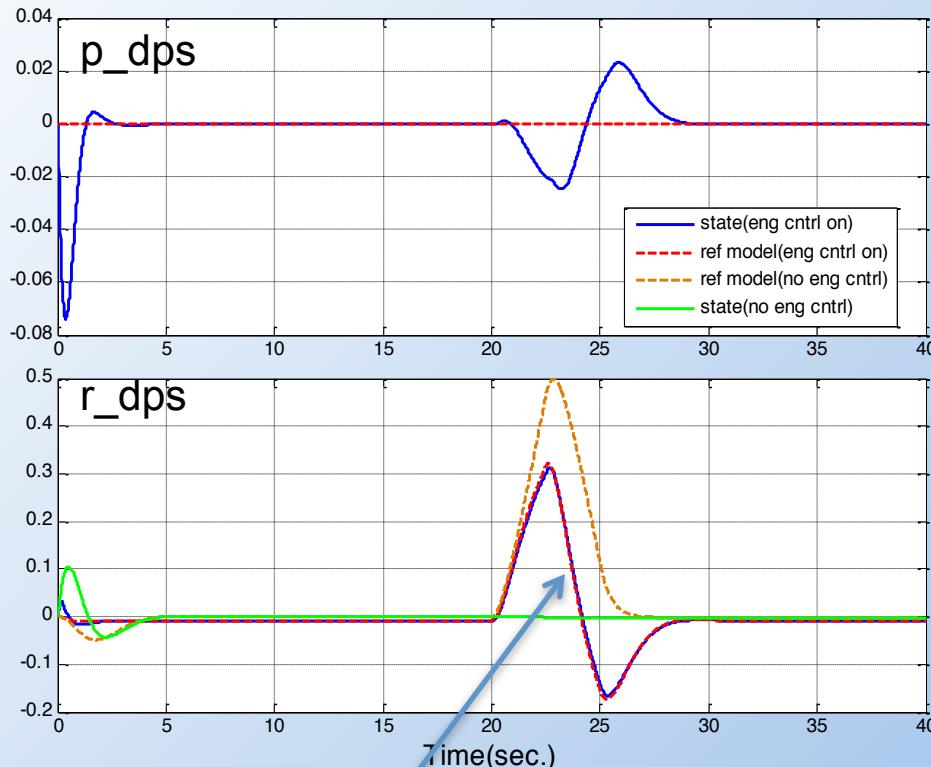


# Differential Thrust Control

(Rudder Locked at Trim, Pedal Input)



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**Restores Model-Following (Diff Thrust functions as Rudder)**

- The blue curve tracks the red curve, but the green curve does not track the orange curve.

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# Differential Thrust Control

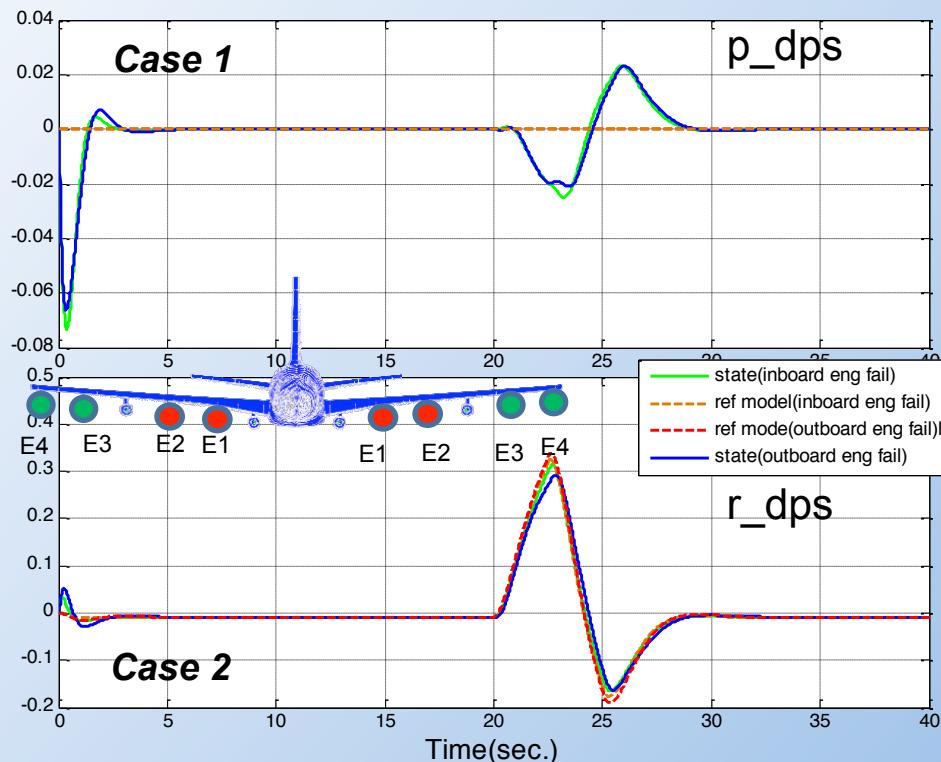
(Rudder Locked at Trim, Pedal Input)



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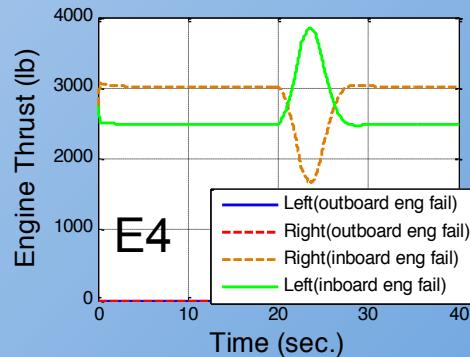
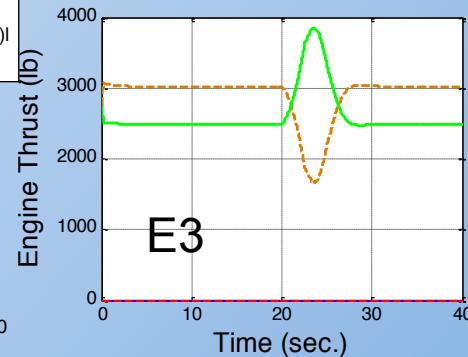
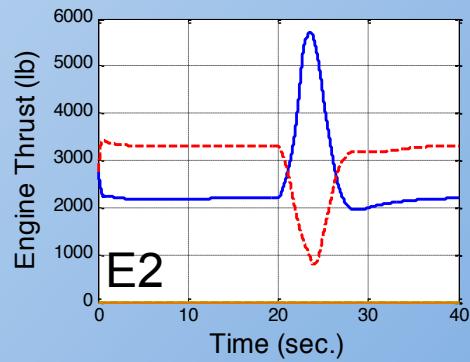
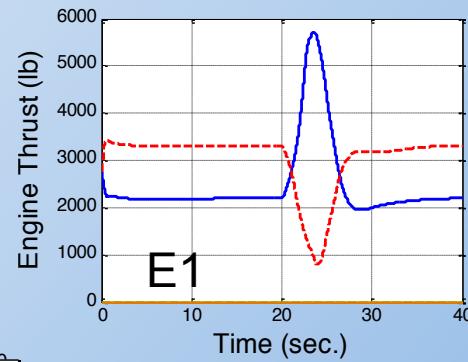


Symmetrical  
Engine Failures



Case 1: Two Failed Outboard Engines

Case 2: Two Failed Inboard Engines



**Distributed control allows for symmetrical multi-engine failure without loss of vehicle directional stability.**

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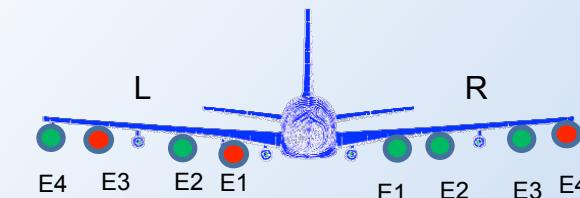


# Differential Thrust Control

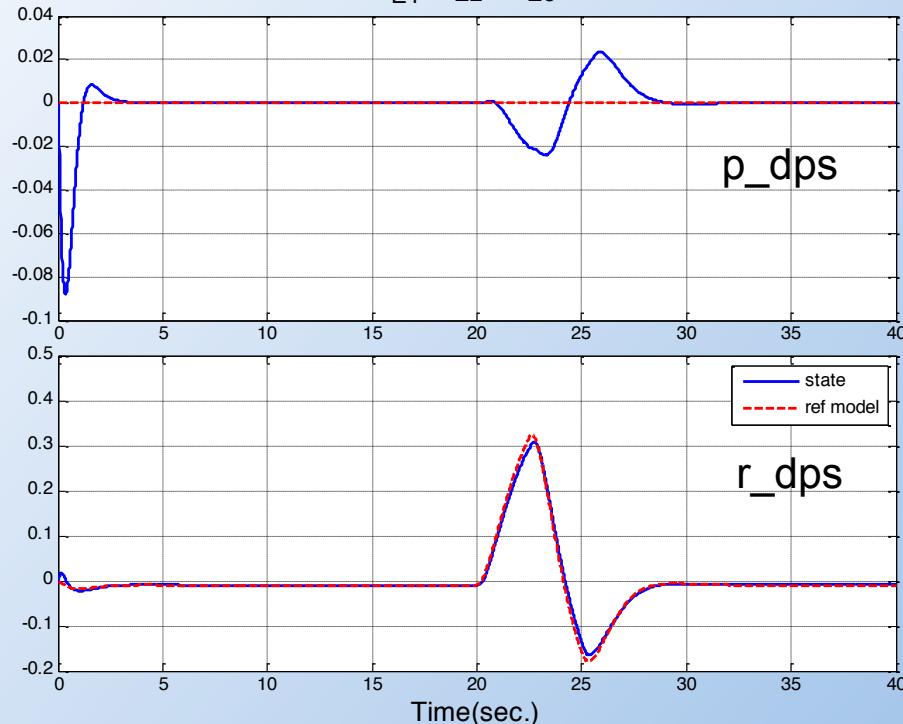
(Rudder Locked at Trim, Pedal Input)



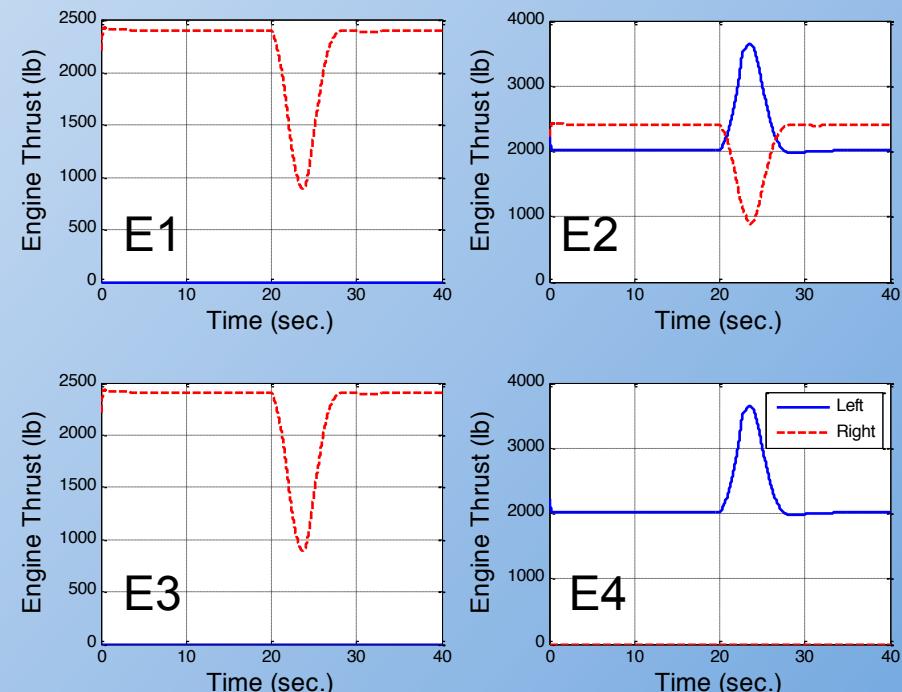
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## Asymmetrical Engine Failures



Failed Engines: L(E1), L(E3), and R(E4)  
(Engines are numbered from the wing root outward)



**Distributed control allows for asymmetrical multi-engine failure without loss of vehicle directional stability.**

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# Rudder Sizing Analysis at Take-Off All Four Engines on the Right Failed

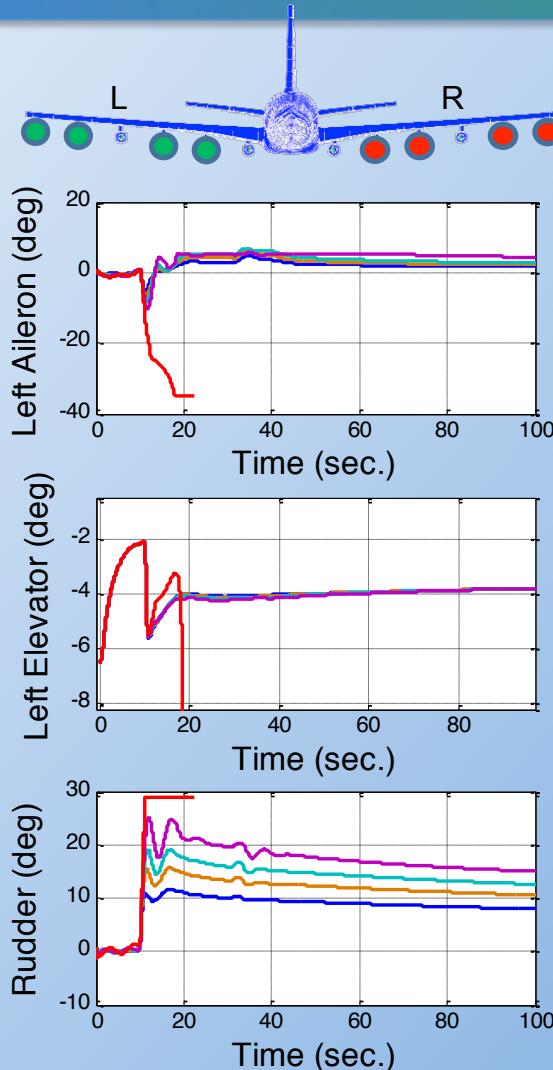
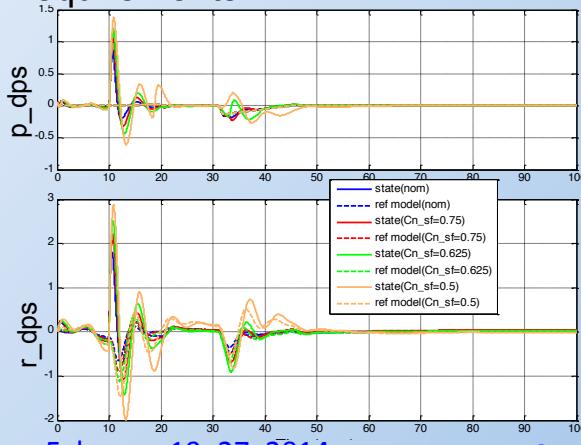


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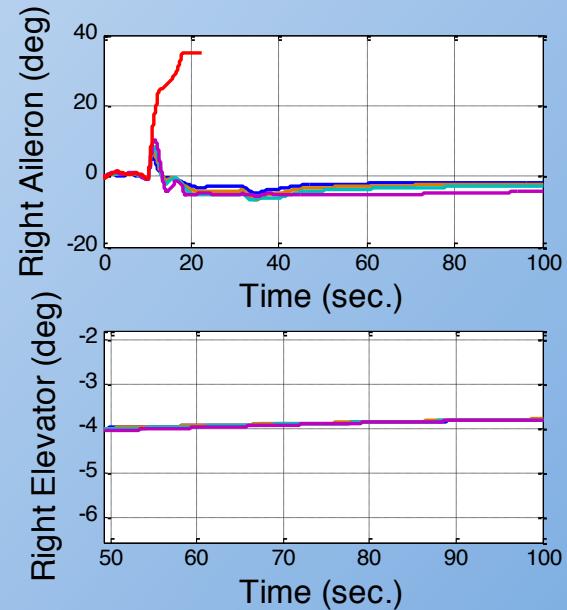
Scale down  $C_n$  until max required rudder deflection reaches 20 deg (2/3 max deflection) for take-off maneuver at (20ft, mach .28) with four failed engines on the right side(i.e., unintended diff thrust).

This occurs at 62.5%: estimate range of allowable reduction in tail size to be between 62.5% and 75% to account for complex variations in  $C_n$  coefficients with tail size.

Aero needed for accurate sizing requirements.



Mach .28, Alt.=20ft



Legend:

- Nom
- Cn\_sf\_0.75
- Cn\_sf\_0.625
- Cn\_sf\_0.50
- Cn\_sf\_0.25

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# Dissemination of Knowledge



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Taken at Ames Unitary Wind Tunnel, August 2013.

Andrew Tsoi, Aero. Academy  
Natalia Nguyen, EAP Program  
Darren Hau, EAP Program  
Charles Perkins, EAP Program

William Nguyen, EAP Program  
Michael Oberti, EAP Program  
Jonathan Tynan, HS Volunteer



## Academic Meetings

- OpenVSP Workshop 2013
- Leaptech 2013
- Stanford Aircraft Design Seminar 2014

## Education Outreach

- Six student interns (summer 2013)
- One HS Volunteer (summer 2013)
- One independent study (Winter 2014)

## Publications

- Reynolds, A. Tsoi, N. Nguyen. "Wing Shaping Control With Distributed Propulsion For Reduced Fuel Burn," Submitted to AIAA Applied Aero 2014.
- M. Oberti, K. Reynolds, N. Nguyen, "Min Fuel to Climb Trajectory Optimization," Submitted to AIAA Applied Aero 2014.
- Tsoi, A., Reynolds, K. "Aeroelastic Modeling of a 2D Flexible Wing Using Distributed Propulsion Control with Galerkin Method," ERN Conference, 2014.

## Invention Disclosure

- "Wing Shaping Concepts Using Distributed Propulsion." Nguyen, N., Reynolds, K., and Ting, E.

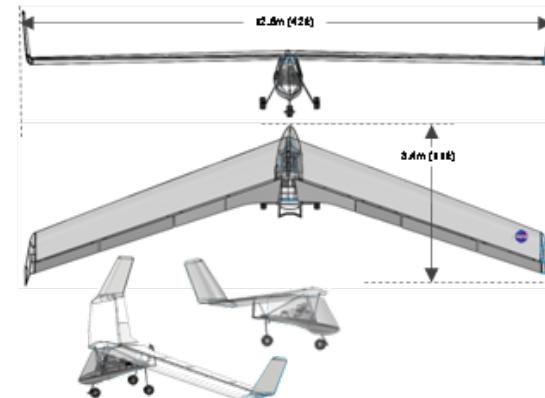


# Next Steps



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- Perform high fidelity aero-propulsive-elastic modeling and simulation of a flexible wing distributed propulsion aircraft
  - NASA GRC involvement with electric propulsor modeling
  - NASA GRC involvement with predicting fuel consumption
- Demonstrate L/D improvements using differential thrust control and trajectory optimization on a UAS platform
  - NASA Armstrong involvement to flight-test PTERA UAS with the help of Area-I
- Develop control algorithms for distributed propulsion fast response electric propulsors for use on commercial aircraft
  - NASA Langley involvement with system and performance analysis
  - Boeing Research on flight dynamic modeling to include wing flexibility for nonlinear control law design





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